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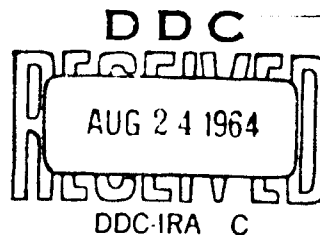
STUDY OF TITANIUM ALLOY TANKAGE AT CRYOGENIC TEMPERATURES

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STUDY OF TITANIUM ALLOY TANKAGE AT CRYOGENIC TEMPERATURES

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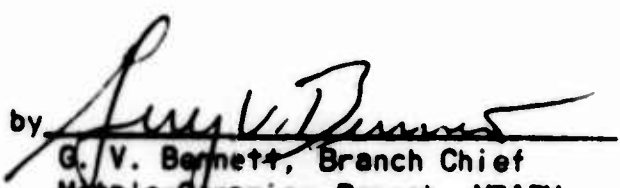
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METALS-CERAMICS BRANCH



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ABSTRACT

A reliable design for high performance, light weight tankage for cryogenic liquid propellants, including liquid hydrogen, is a critical requirement in future spacecraft. Accordingly, a project was initiated to develop titanium pressure vessel fabrication and welding methods. Using Ti-6Al-4V and Ti-5Al-2.5Sn alloys and incorporating three weld designs, a total of eight 16-inch diameter pressure vessels were manufactured and burst tested at temperatures between ambient and -423°F (-253°C). In addition, three 30-inch cylinders of sandwich construction were fabricated and tested under selected thermal gradients. The results showed that resistance or fusion welded Ti-6Al-4V tankage can be manufactured and used at temperatures between ambient temperature and -320°F (-196°C). Further work is necessary to develop titanium tankage for liquid hydrogen applications. The compressive strengths of sandwich cylinders varied very little within the range of the thermal gradients investigated. Information on the fabrication and testing methods as applied to titanium tankage is presented in this report. The possible causes of premature failure at -423°F (-253°C) and the subject of "texture strengthening" are briefly discussed.

I. INTRODUCTION

In the development of spacecraft, the demand for suitable engineering materials for cryogenic applications is becoming increasingly critical. In particular, the use of propellants such as liquid oxygen and liquid hydrogen poses a serious tankage material selection problem. For economic reasons, the tankage material must be formable and weldable by conventional manufacturing methods. The tankage must possess a high strength-to-weight ratio and uphold its structural integrity under high stresses at near absolute zero temperatures. In addition, the tankage material must be corrosion resistant and chemically compatible with the liquid fuel.

Of the commercially available metallic materials, the titanium alloys can best satisfy these requirements. Within this alloy system, the best candidate material is the Ti-6Al-4V alloy. Another alloy, Ti-5Al-2.5Sn, was considered to be the alternate material. Accordingly, a program was initiated to determine the performance of Ti-6Al-4V by manufacturing subscale pressure vessels and cylinders and subjecting them to structural test. Specifically, this program was designed to achieve the following objectives.

- A. Generate manufacturing and process data leading to fabrication of full scale tankage.
- B. Establish weld design and design allowables for each of the three weld designs (Figure 1) on the basis of pressure vessel performance at cryogenic temperatures.

1. INTRODUCTION (Cont'd.)

- C. Determine the possible use of sandwich construction for cryogenic tankage.
- D. Determine the effect of thermal gradients on the buckling characteristics of sandwich cylinders.

At the request of the AST Structures Branch, this work was originally conducted in conjunction with the proposal input effort for the RIFT Program, Reference 1.

2. MATERIALS

The material requirements for the fabrication of 30-inch diameter cylinders, 16-inch diameter pressure vessels, and fixtures are specified in Douglas Drawing Nos. IA00089, IA01246, and IA36574, and are appended in Appendices IA, IB and IC, respectively. Information on the procurement source, material history, chemical compositions, vendor certified mechanical properties, and other pertinent materials data are given in Appendix ID.

3. PROCEDURE

3.1 Pressure Vessel Fabrication

All pressure vessels were fabricated in accordance with the design requirements specified in Douglas Drawing No. IA01246 and IA36574. The six Ti-6Al-4V test domes used in this study were available from a previous titanium dome-forming program, Reference 2. Two additional domes, made from annealed Ti-5Al-2.5Sn sheets, were formed on the

3. PROCEDURE (Cont'd.)

Cincinnati Hydroform Machine located at the Torrance Facility. In preparation for forming, the dome blanks were circle-sheared and the edges deburred by hand polishing. A mild steel back-up sheet, 0.125 inches thick, was circle-sheared and placed between the die cavity and the dome blank.

This arrangement increased the rigidity in the dome flange area and reduced the buckling tendencies. By a single draw operation, the domes were successfully formed. No stress relieving or interstage annealing was necessary. Similarly, the heavy domes, Part No. 1A1246-5, were fabricated from commercially pure titanium sheets, 0.150 inches thick. The pressure vessel design called for a heavy dome on the opposite end of the test section so that failure from hydrostatic burst test would be confined to the proper location.

The cylinders were made from Ti-6Al-4V sheets, 0.050 inches thick, by roll forming. Subsequently, the longitudinal edges were trimmed to the desired diameter of 16 inches and joined by a fusion weld. Because of the difference in wall thickness between the heavy dome (0.150 in.) and the cylinder (0.050 in.), a tapered transition ring was required. This part was made, following the same procedure for fabricating cylinders. Various fabricated components of the three pressure vessel designs are shown in Figures 2, 3, and 4.

To meet the stringent weld mismatch tolerance requirements, each pressure vessel component required sizing prior to assembly welding. The mechanical sizer, Figure 5, was used to size the cylinders through application of external force by a hydraulic press. The hemispherical domes

3. PROCEDURE (Cont'd.)

were sized by a pneumatic sizer, Figure 6.

3.2 Shielding

Because of the high affinity of titanium for gases at elevated temperatures, the weld zone was shielded with a blanket of inert gas. The shielding equipment consisted of welding torch nozzle through which an inert gas was passed, a trailing shield, and a back-up bar which provided shielding for the back side of the weld.

3.3 TIG Fusion Butt Welding of .050 Gage Sheet

Test panels measuring 6 inches x 12 inches were prepared for welding by wire brushing the mating edges with a stainless steel brush. The edges were then draw-filed and cleaned with acetone. The Sciaky Automatic Arc Voltage Control Power Supply, was used to accomplish the welding. The weld settings were evaluated by inspecting for burn-through, porosity, penetration, and by tensile testing at cryogenic temperatures and metallographic examinations. The current and torch travel speed were adjusted to obtain satisfactory results. The selected weld settings are shown in Table I and a photomicrograph of a typical fusion butt weldment is shown in Figure 7.

3.4 TIG Fusion Butt Welding of .150 Gage Sheet

The 0.150-inch fusion weld test panels were prepared in the same manner as the 0.050-inch panels. The 0.150-inch fusion butt joint consisted of a 60° included angle with a 1/32-inch land. The configuration was later modified to include the "J"-groove as illustrated in Figure 8. Both

3. PROCEDURE (Cont'd.)

joints required a root pass and two filler passes. No filler was used on the root pass. A special trailing shield was constructed to provide inert gas protection during welding, Figure 9. The inert gas, passed through the welding torch, was argon. In two instances, as shown in Table I, the inert gas was a mixture of 75% helium and 25% argon. The gas flow rate was increased until a desirable weld penetration was obtained. Argon was used in the back-up bar and trailing shield. The selected weld settings are shown in Table I.

3.5 Resistance Welding of .050 Gage Sheet

The resistance lap weld test panels, measuring 7 inches x 12 inches, were cleaned by wire brushing and swabbing with acetone. The panels were then welded, using the 200-KVA Sciaky Dekatron Counter-Control Resistance Roll Seam Welder. Weld settings, shielding, and cleaning methods were evaluated, based on the tensile test criteria. The tensile coupon design is shown in Figure 10. Based upon the minimum nugget diameter of 0.180-inches as specified in Drawing No. 1A01246, the heat input was adjusted until the tensile test coupons demonstrated that the weld strength was equivalent or higher than the parent metal strength. The selected weld settings are shown in Table II, and typical macro-sections are shown in Figure 11.

Strap weld test panels, measuring 6 inches x 12 inches with 2-1/4-inch x 12-inch strap, were evaluated in the same manner. Selected weld parameters for strap welds are shown in Table II, and a typical macro-section is shown in Figure 12.

3.6 Welding of Pressure Vessels

Welding of bosses to the heavy closure domes was accomplished in an argon purge chamber (Figure 13) using the manual TIG method. Commercially pure Ti-55A wire was used as a filler metal.

The cleaning methods and weld settings used in welding the pressure vessels were identical to those used for preparing tensile test coupons.

The circumferential fusion welds were made in Fixture No. B6-585968-501 shown in Figure 14. Shielding for the weld was provided by the trailing shield attached to the welding torch and a back-up bar. The shielding gas dew point was monitored on all fusion welds. Measurements were taken at the storage bottle, trailing shield and back-up bar.

Resistance welding was accomplished using the 200-KVA Sciaky Resistance Welder. The weld sections were spot welded at 90° intervals before welding. The shielding method used in resistance welding is illustrated in Figure 15.

The closure weld consisted of joining the tapered ring to the heavy dome. Shielding was accomplished with an envelope of a fiberglass and vinyl assembly which was taped inside the vessel, Figure 16. The taped edges were located far enough from the weld joint in order to avoid out-gassing. Two input and two output lines were connected to the envelope. Dew point checks were made at the exhaust lines until satisfactory purging was accomplished. Purging is considered satisfactory when dew point is -100°F. After the closure weld was completed, the envelope was removed from the cylinder through the bosses.

3. PROCEDURE (Cont'd.)

3.7 Inspection

The fusion welds were inspected by radiographic and dye-penetrant methods. Scattered porosity was occasionally detected in the 0.050-inch longitudinal and 0.150-inch circumferential fusion welds. The major defect in the circumferential fusion weld was at the weld start point where lack of fusion was observed to extend for about 1/4 inch along the root of the weld. A repair technique was developed to cope with this problem.

3.8 Repair Technique

When inspection revealed defects such as lack of fusion, tungsten inclusions, or burn-through, weld repairs were required. The defect area was repaired by grinding with a pneumatic rotary file, cleaning with acetone, and manually TIG welding, using commercially pure titanium wire as a filler metal. Both the face and the root of the weld were carefully shielded. The repaired areas were subsequently inspected to insure that the defects were removed. No repair work was required on the closure weld.

3.9 Room Temperature Burst Test

The burst testing of the titanium pressure vessels was conducted at room temperature, using Corvus Oil as the pressurizing medium. Prior to testing, thickness measurements were made over a 3-inch grid pattern on the cylinder with a Model 21 Vidigage, manufactured by Branson Instruments. The thickness values were within commercial tolerance of $\pm 10\%$. The pressure vessels were initially pressurized to 200 psig to

3. PROCEDURE (Cont'd.)

to check for oil leaks and instrument standardization. Upon standardization, the pressure was reduced to zero, then increased at a uniform rate of 16 psig/sec until failure occurred.

Two pressure vessels (Ti-1, Ti-2) were tested at room temperature, Reference 3. The design of these two pressure vessels was modified, as shown in Figure 17, to accommodate a plate which served as a bulkhead instead of a heavy dome.

A rubber seal was initially used at the interface of the flange and the bulkhead on Pressure Vessel Ti-1; however, the rubber seal proved to be inadequate and failed during the first test. Consequently, the rubber seal was replaced by an EC 1300 adhesive and a rubber-cork composition seal. The pressure vessel was then tested to destruction.

In measuring the internal pressure, a visual pressure gage, Norden Keytey No. 868-3164, with a range of 0-3000 psig and an accuracy of $\pm 5\%$, was read by several observers. In addition, for graphic recording of internal pressure the Stratham pressure transducer, Model No. P-10f-2m-350, with a range of 0-2000 psig and an accuracy of $\pm 1\%$, was connected to a Type S Mosley X-Y recorder with an accuracy of $\pm 0.2\%$. The circumferential deflection of the pressure vessel, as a function of internal pressure, was measured by a girth potentiometer and a deflection transducer connected to the X-Y recorder. An illustration of the room temperature instrumentation and test setup is given in Figure 18.

3. PROCEDURE (Cont'd.)

3.10 Cryogenic Burst Test

The cryogenic temperature tests were conducted at the Douglas, Santa Monica liquid hydrogen facility, Reference 4. The temperature at which each pressure vessel was tested was controlled by the cryogenic liquid used for cooling.

The initial test plan was to burst test all pressure vessels at liquid hydrogen temperature. However, since the first test (Ti-5) at -423°F (-253°C) resulted in an unexpectedly low burst stress level, it was considered advisable to determine the effect of other higher temperatures on the performance of Ti-6Al-4V pressure vessels. The initial objectives were altered to include tests at ambient, dry ice, and liquid nitrogen temperatures. With the experimental setup used for dry ice temperature test, it was extremely time-consuming to achieve temperatures below -100°F (-73°C). Therefore, burst test was conducted when the test temperature reached -80°F (-62°C). Temperature was measured by thermocouples which were attached to the outside surface of pressure vessel. Although the test temperatures were varied, all test setups were identical. A schematic drawing of the cryogenic test setup is shown in Figure 19.

Prior to installation in the cryostat, each pressure vessel was filled with small polyethylene pellets in order to reduce the internal volume. All pressure vessels were immersed in the cryogenic liquid for 30 minutes to insure temperature stabilization. During the 30 minute chill-down, an internal pressure of 100 psig was applied in order to maintain positive internal pressure.

3. PROCEDURE (Cont'd.)

The helium gas used for pressurizing was cooled to test temperature by a network of coils submerged in the cryogenic liquid. Upon stabilization of the test temperature, the pressure was increased until failure occurred. The pressure was recorded by an electrical transducer, manufactured by Statham, with a range from 0-2000 psig and an accuracy of $\pm 1\%$. The Statham pressure transducer was connected to a Leeds and Northrup strip chart recorder, Dual Point Model Speedomax, Type G, Serial Number B62-751509-3-2, with a range of 0 to 10 millivolts and an accuracy of $\pm 1\%$. A visual pressure gage, Heisse Model No. H-15432, with a range from 0-100,000 psig and an accuracy of $\pm 1\%$, was also instrumented for pressure recording.

Pressure Vessel Ti-1A was instrumented to record pressure versus time, and circumferential deflection versus time. The deflection gage, Model DD1AUS, Serial Number 033, with a range of 0-2 inches and an accuracy of ± 0.001 inches was manufactured by Micro-Systems. The pressure deflection history for Ti-1A is recorded in Appendixes 2A, 2B, 2C and 2D.

3.11 Sandwich Cylinder Fabrication and Testing

An investigation was conducted to determine the effect of thermal gradient on the buckling characteristics of sandwich cylinders. Three cylinders 30 inches in diameter and 30 inches in length, were constructed, using the welding techniques described previously. The inner face was 0.050-inch Ti-6Al-4V sheet and the outer face, .020 fiberglass laminate. The core was a honeycomb resin phonolic (HRP), 1/4-inch thick, 3/16-inch

3. PROCEDURE (Cont'd.)

cell diameter, with a density of 4 lb/cu ft. Two layers of 181 fiber-glas cloth were added to the outside of the core. The cylinders were prepared in the following manner:

- A. .050 Ti-6Al-4V sheet was used to fabricate the cylinders according to Drawing No. 1A00089-503. (Appendix 1A).
- B. The titanium cylinders were cleaned by vapor-honing.
- C. The outside surface of the titanium cylinders was primed with HT-424B primer by brushing on a coat approximately 0.003 inches thick. The primed skins were air dried at 78°F (25.6°C) for 30 minutes after curing at 150°F (65.6°C) for one hour.
- D. The HRP core was cut as specified in Drawing No. 1A00089 and degreased according to MIL-T-7003.
- E. HT-424 adhesive, with shear strength of 17 lb/ft², was applied on one surface of the cleaned core, and the core was laid on the outside (primed) surface of the titanium cylinder.
- F. The assembly was vacuum-bagged and cured in an oven at 330°F (166°C) and under 28-inches of Hg for one hour, and cooled to room temperature before the vacuum was released.
- G. Type 181 fiberglass cloth was wrapped around the cylinder and the assembly was again vacuum-bagged and oven cured at 330°F (166°C) for one hour under 28 inches of mercury. Then cooled to room temperature before the vacuum was released.

3. PROCEDURE (Cont'd.)

- H. The top and bottom of the cylinder walls were filled to a depth of 1-1/2 inches with Lefkowitz 109 and cured at 150°F (65.6°C) for one hour.
- I. A Ti-6Al-4V doubler was then laid up along the top and bottom inner periphery of the cylinder. Lefkowitz 109 adhesive was used between the doublers and the outer face.
- J. The top and bottom edges of the cylinder were then milled parallel to each other.

The effect on the cylinder compression properties of three different thermal gradients was investigated. The maximum thermal gradient was achieved by filling the cylinders with liquid nitrogen and heating the outside surface with heat lamps. The temperature of the outside surface was measured by thermocouples, and the temperature of the inside was determined by the liquid nitrogen used for cooling. Hydraulic jacks were used to apply the compressive load to the cylinders, Figure 20.

4. RESULTS

The weld settings used for fabricating pressure vessels are given in Tables I and II. Listed in Table III are the weld tensile strengths at -423°F (-253°C) of the resistance welded Ti-6Al-4V panels as affected by chemical and mechanical cleaning and inert gas shielding.

Tables IV, V, & VI give the uniaxial tensile test results for each of the three joint configurations, excluding the 0.150 fusion butt joint, at

4. RESULTS (Cont'd.)

various test temperatures. The resistance welded coupons tested at -320°F (-196°C) or above always failed in the parent metal. However, at -423°F (-253°C), failure was often in the weld or heat-affected zone. If the failure was in the parent metal, the strength values were lower than the known parent metal strength of 260 KSI. It was suggested that soaking time was the cause of this low strength. (The soaking time is the time a test specimen is held in the test environment before load application).

In order to determine the effect of soaking time on the strength of Ti-6Al-4V, fusion welded tensile coupons, which were readily available, were tested at -423°F (-253°C), for times between 5 to 30 minutes. As the data show in Table VII, a soaking time of 5 minutes developed the expected strength level.

A summary of the burst tests on the titanium pressure vessels is in Tables VIII and IX and a series of illustrations, including the photographs of all eight burst tested pressure vessels, are presented in Figures 21-34.

The titanium sandwich compression test results with thermal gradient data are summarized in Table X. Figure 35 shows a typical 30-inch diameter cylinder which was compression tested at room temperature.

5. DISCUSSION

5.1 A comprehensive discussion on the formability of Ti-6Al-4V sheet as applied to hydroforming 16-inch diameter hemispheres is given in Reference 2. Whereas Ti-6Al-4V requires two drawing operations with an

5. DISCUSSION (Cont'd.)

interstage annealing at 1300°F (704°C), Ti-5Al-2.5Sn is capable of being deep drawn to hemispheres in a single draw. The only difficulty associated with a single draw operation is in the separation of forming dome from the backup material. Since a high pressure is required to separate the mating parts, adequate precautions must be taken. Light tapping or lubrication of the interface facilitates the separation.

No difficulty was encountered in cylinder forming and sizing. A dimensional control of ± 0.005 -inches in the dome or the cylinder diameter can be maintained with the sizing equipment available at Douglas.

5.2 Effect of Cleaning Method on the Resistance Weld Strength at -423°F (-253°C)

As the data in Table III indicate, superior and more consistent weld strengths were developed by shielding, regardless of the cleaning method used. Of the shielded and welded test specimens, there was no significant difference between pickling and wire brushing with respect to weld strength at -423°F (-253°C). Because of simplicity wire brushing was selected as a method of cleaning parts to be welded.

5.3 Weld Strength of Ti-6Al-4V Sheet at Temperatures Between Ambient and -320°F (-196°C)

At temperatures between room temperature and -320°F (-196°C), a joint efficiency of 100% was developed by all three joint designs. This is evident from the fact that all welded coupons failed in the parent metal at strength levels comparable to known material strengths at correspond-

5. DISCUSSION (Cont'd.)

ing temperatures (References 5 and 6).

5.4 Weld Strength of Ti-6Al-4V Sheet at -423°F (-253°C)

As can be seen from the data in Tables IV, V, and VI, the weld strengths were lower than the expected level of 260 KSI at -423°F (-253°C).

Subsequently, an experiment was conducted to determine the effect of soaking time. The results presented in Table VII show that a soaking time of 5 minutes was adequate. The only plausible explanation for the low strength values reported for certain specimens is that the specimens were not soaked for at least 5 minutes at -423°F (-253°C). Therefore, the tensile test data for this temperature are inconsistent and unreliable.

5.5 Performance of Ti-6Al-4V Pressure Vessels at Temperatures Between Ambient and -320°F (-196°C)

The performance of Ti-6Al-4V pressure vessels at room temperature was exceptionally good. A hoop stress of 195 KSI was developed which represents 133% of the tensile strength. The hoop to tensile stress ratio of 133%, Table IX, is significantly higher than the theoretical ratio of 115%. This is probably a result of the texture hardening phenomenon. As the photograph in Figure 22 shows, considerable deformation had occurred. At -80°F (-62°C), the burst strength was 208 KSI which represents at least 125% of the tensile strength of Ti-6Al-4V sheet (Table IX).

At -320°F (-196°C) Pressure Vessel Ti-1A failed at a hoop stress of 252 KSI. Visual examination of this pressure vessel, Figure 26, after the

5. DISCUSSION (Cont'd.)

test revealed that an undersize resistance weld nugget resulted from a resistance weld being superimposed directly upon a longitudinal fusion weld. This condition decreased the electrical resistance of the welding system and resulted in an abnormally small nugget size, Figure 27.

As can be seen in Figure 28, the premature failure of Pressure Vessel Ti-1A at -320°F (-196°C) is reflected in the stress-strain curve, which shows that the failure occurred at a plastic strain of approximately 0.1%. For Ti-1A the ratio of hoop stress to uniaxial tensile strength is 118% (Table IX), which is somewhat higher than the theoretical value of 115%. In comparison, Pressure Vessel Ti-2A, Figure 29, which was also tested at -320°F (-196°C), developed a hoop stress of 281 KSI and a hoop-to-tensile stress ratio of 132%. The data suffice to demonstrate that (1) Pressure Vessel Ti-1A failed prematurely in spite of its high hoop-to-tensile strength ratio, (2) the high ratio is attributed to texture hardening and (3) texture hardening was operative even at a low plastic hoop strain of less than 0.2%.

Figure 28 also shows the effect of temperature on the shape of hoop stress-strain curve. A typical modulus in uniaxial tension at room temperature is 16.5×10^6 psi, indicated by a dotted line. In a 2:1 stress field, the elastic moduli are 23×10^6 psi and 30×10^6 psi at room temperature and -320°F (-196°C), respectively.

5.6 Performance of Ti-6Al-4V Pressure Vessels at -423°F (-253°C)

Pressure Vessels Ti-4 and Ti-5, which were tested at -423°F (-253°C), did

5. DISCUSSION (Cont'd.)

not develop the expected burst strength, Table VIII. In Pressure Vessel Ti-4, the origin of failure appeared to be at the weld start-stop point. At this site (indicated by an arrow in Figure 32), an overlap of 3/4 inches in the circumferential resistance weld was found, Figure 33. Visual examination of Pressure Vessel Ti-5 revealed no indications as to the origin and cause of premature failure.

A photoelastic analysis was made to determine if the boss area in the heavy dome were responsible for the low burst strength. However, the results showed that the magnitude of stresses due to design discontinuities was relatively low and insignificant, Reference 7.

In an attempt to redistribute the inherent residual stresses in the pressure vessel, Ti-6 was instrumented and proof stressed at room temperature to 0.05% circumferential deformation when failure occurred, Figure 34. Had the proof test been successful, this pressure vessel would have been burst tested at -423°F (-253°C) as a duplicate of Ti-5. The unexpected failure of Ti-6 was caused by a local thin section (0.041 inches) in the cylinder wall of 0.047 inches in nominal thickness. Apparently this spot escaped detection by a 3-inch grid system over which Vidigage thickness measurements were made before proof testing. Because of this incident, the subsequent pressure vessels scheduled for test were remeasured over a 1-1/2-inch grid system scribed on the cylinder.

5. DISCUSSION (Cont'd.)

5.7 Preferred Orientation

In order to determine the degree of preferred orientation in the material used, samples from Pressure Vessel Ti-2, after burst testing, were submitted to TMCA (Titanium Metals Corporation of America), Reference 8. Using the direction of the weld as reference, (0001) pole figures were determined for the base metal and the weld. For the base metal, the data showed that the basal plane (0001) rotated approximately 28-30 degrees out of the plane of the sheet. It is of interest to note that in the weldment, the (0001) plane lay in the plane of the sheet. In the heat-affected zone the texture became mixed, i.e., a mixed pattern of parent metal and weld textures was shown.

5.8 Texture Strengthening

The R value for Ti-2 was calculated by Titanium Metals Corporation of America (Reference 8), and was found to be approximately 1.5. The R value is the ratio of width strain to thickness strain, and is a measure of the thinning resistance of sheet metal. Even if the tensile yield stress of a material is low, the thinning resistance can develop a high yield strength under biaxial tension stresses. If a sheet is to yield under balanced biaxial tension stress, it must do so by thinning. The marked strengthening in the through-thickness direction under these conditions is termed "texture hardening". After Titanium Metal Corporation of America had calculated the R value of Ti-2, they independently conducted an evaluation of texture hardening (Reference 9). As a result, the average value of R for Ti-6Al-4V was determined to be 0.83. In

5. DISCUSSION (Cont'd.)

Reference 9, the pole figures for the Ti-6Al-4V alloy were determined from three different heats. In each case, the basal poles were split into two orientations which were rotated approximately 30 degrees from the normal to the sheet plane. The texture of the three heats was similar to that of Pressure Vessel Ti-2, but their respective R values measured were considerably different; therefore, it appears that the R ratio is not correlated to the preferred orientation in 6A-4V titanium sheet.

5.9 Sandwich Cylinders

Some exploratory work was done to determine the effect of thermal gradients on the buckling characteristics of sandwich cylinders, Reference 10. It may be seen in Table X and Figure 35 that the thermal gradients had no significant effect on the ultimate load intensities of the sandwich cylinders.

6. CONCLUSIONS

1. Ti-6Al-4V and Ti-5Al-2.5Sn alloys are formable at room temperature in the mill-annealed condition. Deep drawing of the Ti-5Al-2.5Sn domes may be accomplished by hydroforming in one stage and no interstage annealing cycle is required.
2. Sizing is readily accomplished. The circumference may be increased as much as 0.010 inch/inch during the sizing operation.
3. The Ti-6Al-4V and Ti-5Al-2.5Sn alloys are weldable and require no post weld thermal treatment. Close tolerances must be maintained on mating

6. CONCLUSIONS (Cont'd.)

components for a satisfactory weld.

4. A weld efficiency of 100% can be developed in a resistance or TIG fusion welded Ti-6Al-4V sheet material at cryogenic temperatures down to -320°F (-196°C).
5. At cryogenic temperatures down to -320°F (-196°C), Ti-6Al-4V pressure vessels developed a hoop stress level of 125% to 135% of the uniaxial tensile strength. This high percentage is attributed to the benefits derived from texture hardening.
6. At -423°F (-253°C) premature failure occurred in the pressure vessels prior to any plastic deformation. Uniaxial tensile results, at the same temperature, on the resistance-welded coupons also exhibited atypical low values. The exact mechanisms or metallurgical changes responsible for this behavior are not fully understood.
7. The compressive or buckling strength of the sandwich cylinders was not affected by the thermal gradients investigated.

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6. Douglas Materials Manual, "Cryogenic Properties for Annealed ELI 6Al-4V Titanium Sheet, 0.025 Inch Thick," Page Ti 2.1.2.2.1.
7. McIver, R.W., Titanium Pressure Vessel Test, Douglas Aircraft MP Report 20,359, July 12, 1963.
8. Hatch, A.J. "Ti-6Al-4V Pressure Vessel From Douglas Aircraft," Internal TMCA memorandum, November 5, 1962.
9. Hatch, A. J. "Texture Hardening of Titanium Alloys: Evaluation of Commercially Produced Sheet" Titanium Metal Corporation of America, Progress Report #1, March 5, 1963.
10. Hess, Q., Honeycomb Cylinder Ultimate Compression Buckling Load Thermal Differential Stress Test, SM 41147 November 1962.

8. DATA

PCR Book No. 17517

Physical Test Lab Case Sheet Nos.	23602	28118	23665
	23646	21253	11812
	25658	29217	23666
	23658	23611	23664
	23665	23643	23523
	23641	23642	23637
	23633	23634	23635
	23636	23631	23613
	23630	28636	

8. **DATA** (Cont'd.)

Photo Stress Lab Case Sheet No. 24298 23645

Shop Order 80295-800

EW0 52728

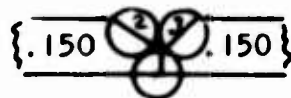
JW0 0003

TABLE 1

FUSION WELD SETTINGS FOR 16" DIA
TITANIUM PRESSURE VESSELS



FUSION - BUTT
TYPE 1



FUSION - BUTT, 60° V-GROOVE
TYPE 2A



FUSION - BUTT J-GROOVE
TYPE 2B

JOINT TYPE	EXAMPLE WELD (1)	AMPS	VOLTS	IPM TORCH TRAVEL	TORCH CFH	TRAIL CFH	BACK-UP CFH	FILLER WIRE SPEED
1	-2	126	8.5	14	35A	35A	5A	30 IPM
	-3 to 9	97	7.7	21	40A	120A	40A	
	-41 to -49	97	7.5	21	40A	200A	160A	
	-49 to -45	110	7.5	21	40A	200A	160A	
	-47 to -49	65	8.5	10	40A	60A	160A	
2A	425 to -5	1. 170	9.0	9.0	100 H, A	160A	160A	60 IPM 60 IPM
	-9 to -425	2. 110	8.0	7.5	40A	160A	160A	
		3. 110	8.0	7.5	40A	160A	160A	
2B	-425 to -9	1. 120	9.0	7.25	40 H, A	120A	160A	60 IPM 60 IPM
		2. 110	8.0	7.5	40A	120A	160A	
		3. 110	8.0	7.5	40A	120A	160A	

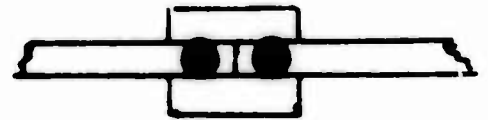
A = Argon Gas; Dew Point = -100°F or Better *

H, A = 75% Helium, 25% Argon; Dew Point = -100°F or Better *

(1) See Appendix 1B for detailed description

* - 100°F = -73.3°C

TABLE 11

RESISTANCE WELD SETTINGS FOR 16" DIA.
TITANIUM PRESSURE VESSELS

	RESISTANCE -- LAP	RESISTANCE - BUTT STRAP
Heat Setting	2B	3C
Weld PH Shift %	20	20
Weld Vernier %	6.0	8.0
Top Pres. Gauge	2,500	2,500
Back Pres. Gauge	1,000	1,000
Constant Pressure	Yes	Yes
Heat (Cycles)	6	6
Weld Interval (Impulses)	2	2
Cool(Cycles)	.5	.5
Squeeze (Cycles)	30	30
Forge Initiation	Beginning of Weld	Beginning of Weld
Hold Cycles	30	30
Distance Between Arms		
At Welding Position (In.)	3 3/4	3 3/4
Throat Depth (In.)	51	51
Drive	Intermittent	Intermittent
Forge (Cycles) Seam Weld	50	50
Motor Speed R.P.M.	54	54
Inches/Min.	3 1/2	3 1/2
Motor Run Time (Cycles)	22	22
Spots Per Inch	7	8
% Overlap	50%	50%
Electrode Alloy (Top)	M3	M3
Dia. of Electrode(Top),(Bottom)	13", 9 1/4"	13", 9 1/4"
Radius of Electrode (Top)	12	12
Electrode Alloy (Bottom)	M3	M3
Radius of Electrode (Bottom)	6"	6"
Thickness of Wheels	3/4"	3/4"
Phase Operation	30	30
Argon Shielding (CFH)	12	12

TABLE III

ROLL SEAM RESISTANCE WELD STRENGTH OF .050 GAGE Ti-6Al-4V SHEET AT
-423°F (-253°C)

WELD DESIGN	CLEANING METHODS	WELD STRENGTH (PSI)*
Lap	Wire Brush, Shielded	204,100
		199,800
		201,400
		200,800
		192,800
Lap	Wire Brush, No Shielding	198,400
		191,900
		167,000
Butt-Strap	Wire Brush, No Shielding	197,800
		220,500
		234,700
		185,300
		194,700
Butt-Strap	Wire Brush, Shielded	233,800
		241,700
		226,500
Lap	Pickled, Shielded	192,500
		203,100
Lap	Pickled, No Shielding	189,100
		189,100
Butt-Strap	Pickled, Shielded	225,100
		243,500
		243,300
		238,500
		244,500
Butt Strap	Pickled, No Shielding	258,000
		236,100
		226,800

* Tested in the transverse direction with respect to weld direction.

All specimens failed adjacent to the weld nugget.

TABLE IV

FUSION BUTT-WELD STRENGTH OF .050 GAGE Ti-6Al-4V SHEET AT
CRYOGENIC TEMPERATURES

(NO FILLER)

TEST TEMPERATURE	WELD STRENGTH (PSI)*	FAILURE LOCATION**
R.T.	147,900	PM
	151,100	PM
	150,400	PM
	145,400	PM
	145,600	PM
	<u>147,700</u> (Average)	
-100°F (-73.3°C)	165,300	PM
	168,200	PM
	168,200	PM
	164,300	PM
	<u>167,700</u>	PM
	<u>166,700</u> (Average)	
-320°F (-196°C)	214,200	PM
	214,700	PM
	192,200	PM
	212,600	PM
	<u>212,300</u>	PM
	209,200 (Average)	
-423°F (-253°C)	249,000	PM/HAZ
	247,900	PM
	223,100	PM/HAZ
	248,500	PM
	248,900	PM
	242,200	PM
	251,900	PM/HAZ
	254,900	PM/HAZ
	253,200	PM
	243,800	PM
	251,600	PM
	238,100	PM/HAZ
	236,360	PM/HAZ
	<u>237,360</u>	PM/HAZ
	244,800 (Average)	

* Tested in the transverse direction with respect to weld direction

** PM = Parent Metal, HAZ = Heat Affected Zone

TABLE V

ROLL-SEAM RESISTANCE LAP-WELD STRENGTH OF .050 GAGE Ti-6Al-4V SHEET
AT CRYOGENIC TEMPERATURES

TEST TEMPERATURE	WELD STRENGTH (PSI) *	FAILURE LOCATION**
R.T.	146,800	PM
	<u>148,000</u>	PM
	147,400 (Average)	
-100°F (-73.3°C)	167,700	PM
	<u>165,400</u>	PM
	166,600 (Average)	
-320°F (-196°C)	214,300	PM
	<u>212,200</u>	PM
	213,200 (Average)	
-423°F (-253°C)	206,800	PM
	198,000	PM
	209,900	PM
	211,100	PM
	228,600	PM, Weld
	<u>225,200</u>	PM, Weld
	213,300 (Average)	

* Tested in the transverse direction with respect to weld direction.

** PM = Parent Metal

TABLE VI

ROLL-SEAM RESISTANCE BUTT-STRAP WELD STRENGTH .050 GAGE TI-6Al-4V
SHEET AT CRYOGENIC TEMPERATURES

TEST TEMPERATURE	WELD STRENGTH (PSI)*	FAILURE LOCATION
R.T.	144,800	PM**
	144,200	PM
	140,100	PM
	144,400	PM
	143,400(Average)	
-100°F (-73.3°C)	166,400	PM
	160,700	PM
	158,900	PM
	165,500	PM
	164,300	PM
	163,500(Average)	
-320°F (-196°C)	214,500	PM
	213,200	PM
	213,800(Average)	
-423°F (-253°F)	233,800	HAZ ***
	241,700	HAZ
	226,500	HAZ
	234,400(Average)	

* Tested in the transverse direction with respect to weld direction

** Parent Metal

*** Heat Affected Zone

TABLE VII

UNIAXIAL TEST RESULTS 6Al-4V TITANIUM ALLOY
(FILLER-FUSION)*

TEST TEMPERATURE	FAILURE STRESS (PSI)**	FAILURE *** LOCATION	SOAK TIME
-423°F (-253°C)	269,705	PM	30 Min.
	261,620	PM	5 Min.
	263,400	PM	10 Min.
	262,160	PM/HAZ	10 Min.
	262,800 (AVERAGE)		

* TIG weld using commercially pure filler wire

** Tested in the transverse direction with
respect to weld direction

*** PM = Parent Metal

HAZ = Heat Affected Zone

TEMP 70°F 70°F 70°F -80°F -320° 1 -320° 1 -320° 1 -423° 1 -423° 1 -423° 1

TABLE VIII
PRESSURE VESSEL TEST RESULTS

MATERIAL CYLINDER DOME	JOINT* DESIGN	VESSEL NO.	TEST TEMPERATURE	YIELD PRESSURE .2% OFFSET	ULTIMATE PRESSURE	YIELD STRESS .2% OFFSET	ULTIMATE STRESS
6A1-4V	-501	Ti-1	70°F, (21°C)	1072 PSI	1240 PSI	172 KSI	195 KSI
6A1-4V	-501	Ti-2	70°F, (21°C)	1050 PSI	1240 PSI	168 KSI	195 KSI
6A1-4V	-501	Ti-1A	-320°F, (-196°C)	1530 PSI**	1480 PSI	260 KSI	252 KSI
6A1-4V	-501	Ti-2A	-320°F, (-196°C)	-----	1650 PSI	-----	281 KSI
6A1-4V	-503	Ti-3	-80°F, (-62°C)	-----	1210 PSI	-----	208 KSI
6A1-4V	-503	Ti-4	-423°F, (-253°C)	-----	785 PSI	-----	136 KSI
6A1-4V	-505	Ti-5	-423°F, (-253°C)	-----	1240 PSI	-----	221 KSI
6A1-4V	-505	Ti-6	70°F, (21°C)	-----	967 PSI	-----	198 KSI

* Refer to Figure 1 for joint design
** Extrapolated

TABLE IX

RATIO OF HOOP STRESS TO UNIAXIAL TENSILE STRESS

TEST TEMPERATURE	VESSEL NO.	UNIAXIAL TENSILE STRESS (KSI) PM	HOOP STRESS AT FAILURE (KSI)	HOOP TO TENSILE STRESS RATIO, %
0°F (21°C)	Ti-1	147	195	133
0°F (21°C)	Ti-2	147	195	133
0°F (21°C)	Ti-6	147	198	135
30°F (-62°C)	Ti-3	166	208	125
0°F (-196°C)	Ti-1A	213	252	118
0°F (-196°C)	Ti-2A	213	281	132
3°F (-253°C)	Ti-4	263	136	51.6
3°F (-253°C)	Ti-5	263	221	84.0

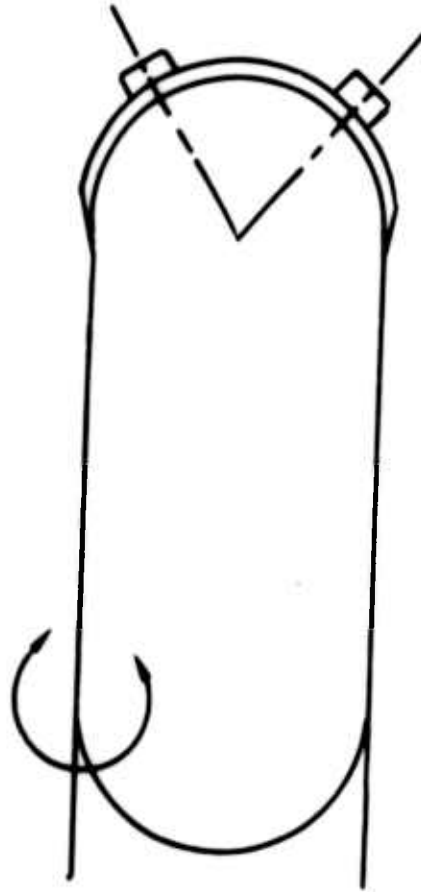
TABLE X

TITANIUM SANDWICH CYLINDERS
THERMAL GRADIENT AND COMPRESSIVE LOAD

CYLINDER NO.	TEMPERATURE (°F)		COMPRESSIVE ULTIMATE LOAD (LB)	ULTIMATE LOAD INTENSITY (LB/IN.)
	INSIDE	OUTSIDE		
1	70(21°C)	70(21°C)	256,000	2720
2	-320(-196°C)	70(21°C)	221,250	2350
3	-320(-196°C)	250(121°C)	270,000	2860

FIGURE 1
TYPICAL TEST SECTIONS

TEST SECTION

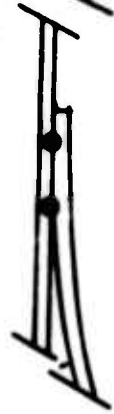


RESISTANCE BUTT STRAP WELD



-501

RESISTANCE LAP WELD



-503

FUSION BUTT WELD



-505

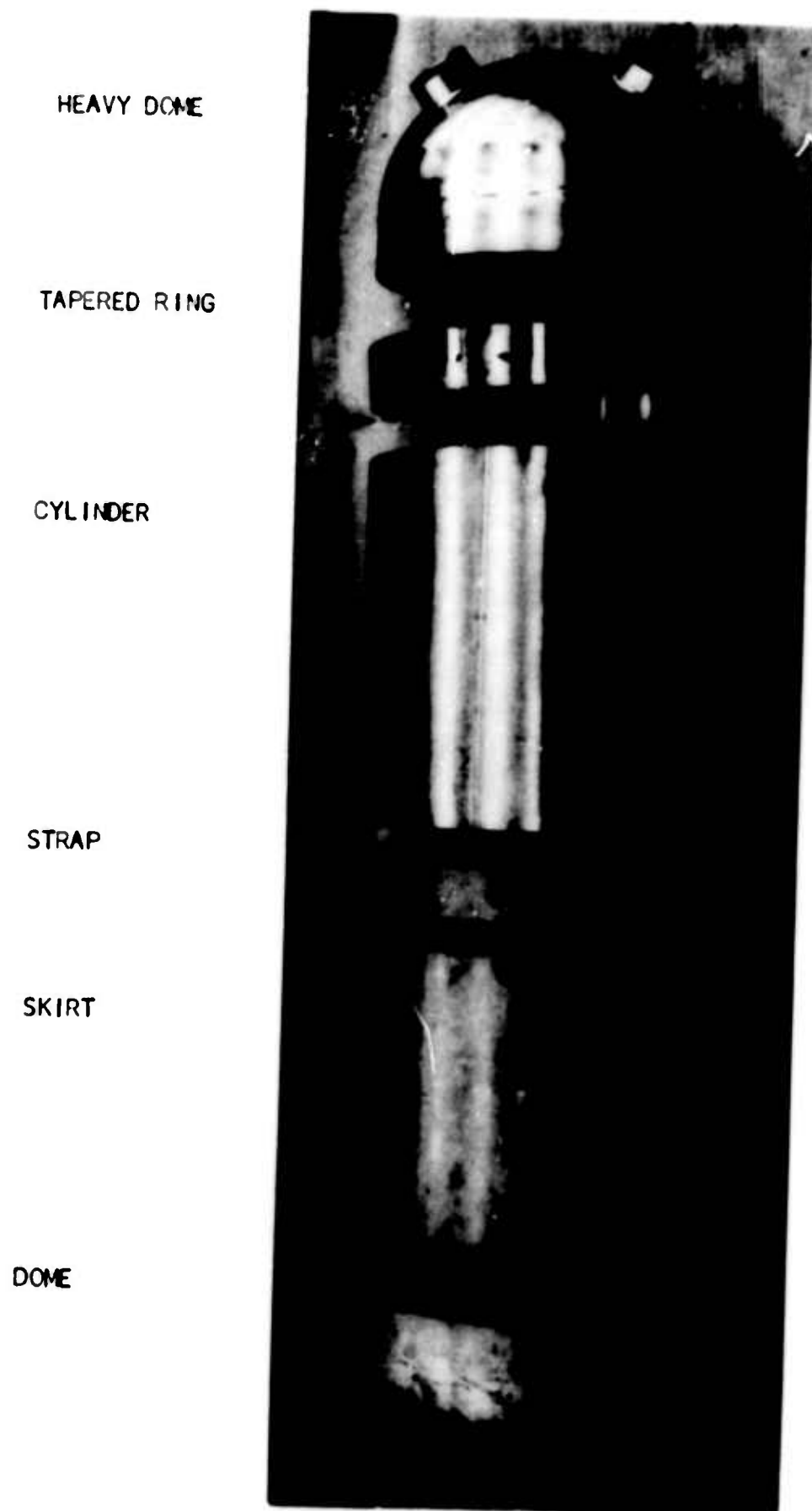


FIGURE 2
COMPONENTS FOR RESISTANCE STRAP WELDED PRESSURE VESSEL

SM 3 77152

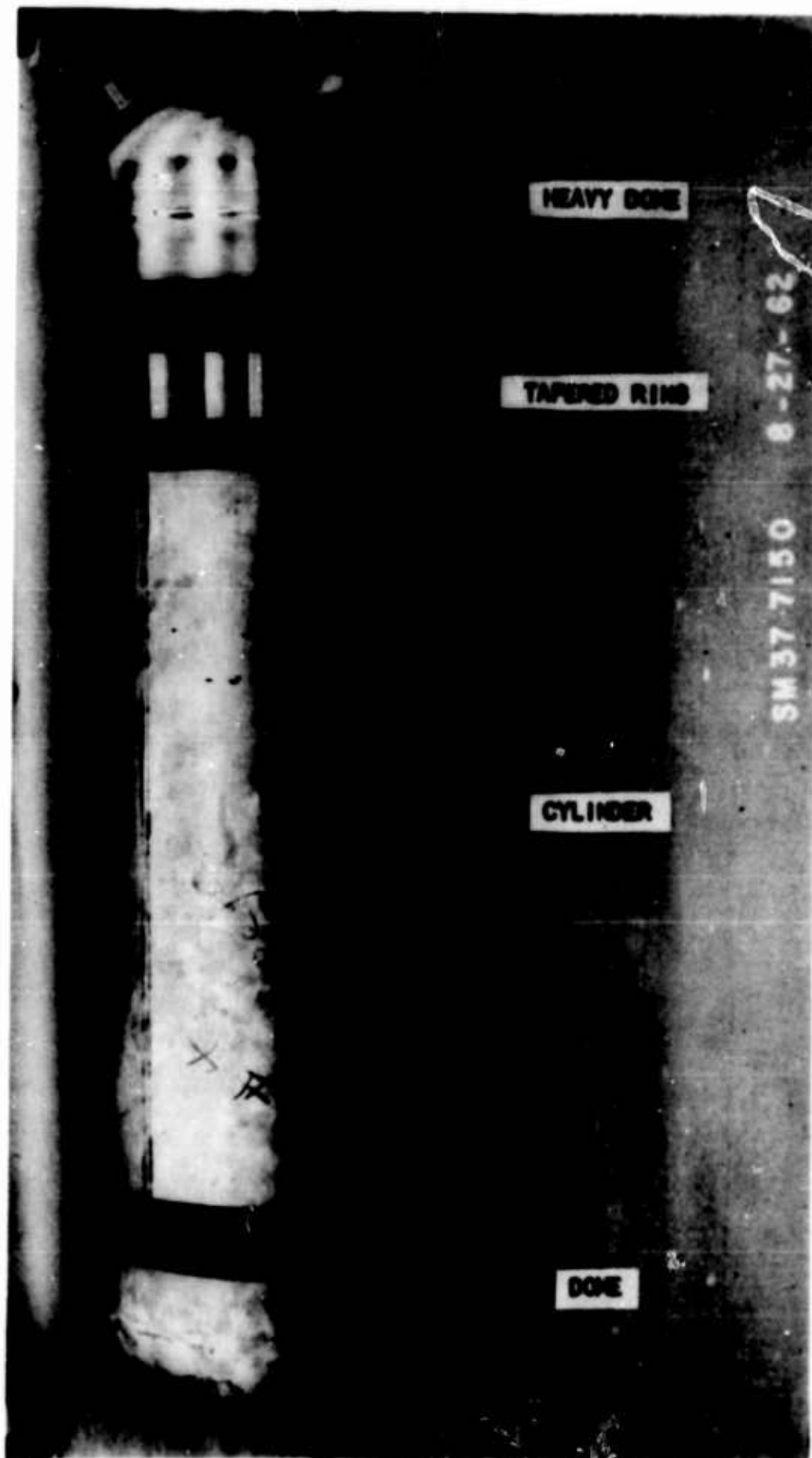


FIGURE 3

COMPONENTS FOR RESISTANCE LAP WELDED PRESSURE VESSEL

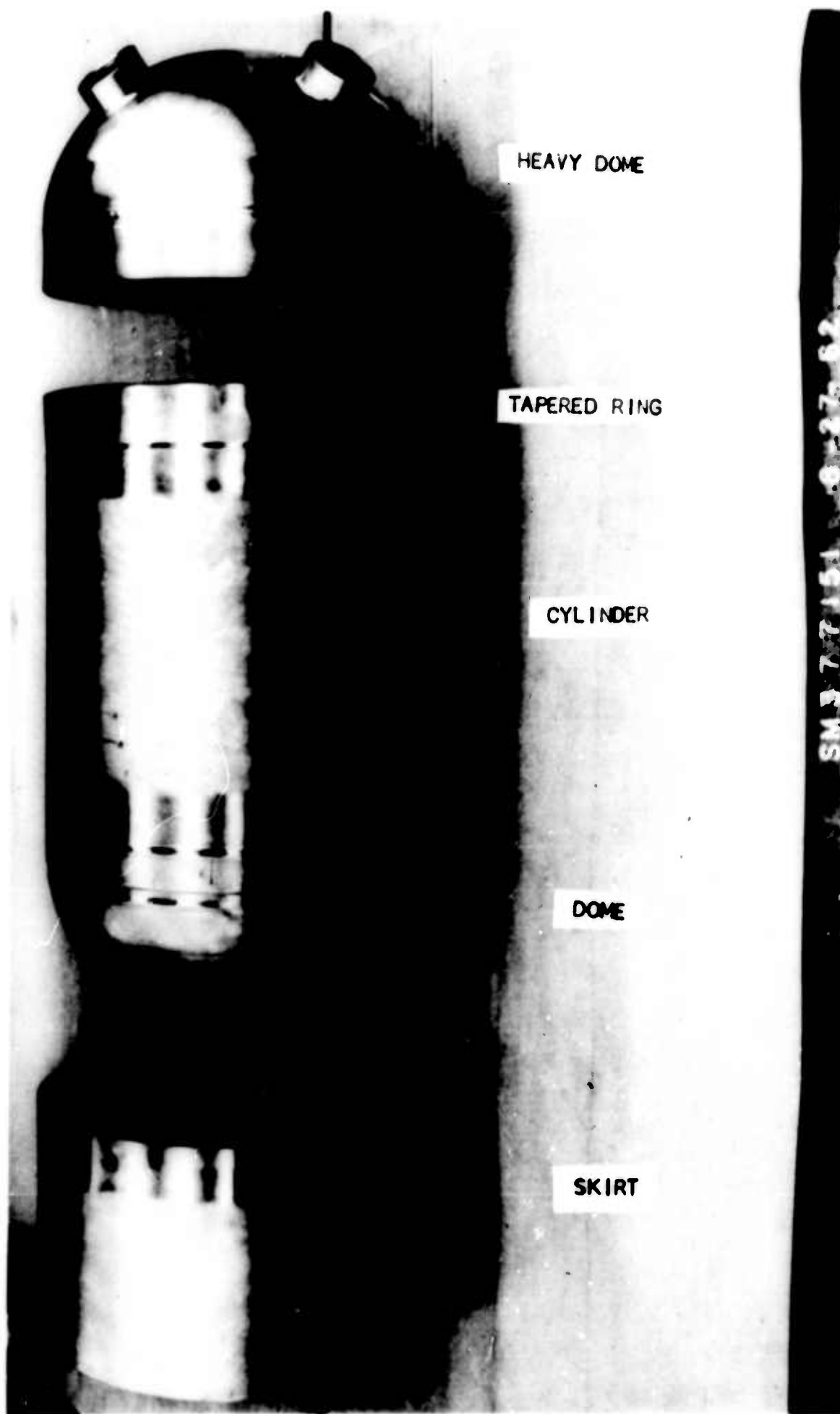


FIGURE 4
COMPONENT FOR FUSION WELDED PRESSURE VESSEL

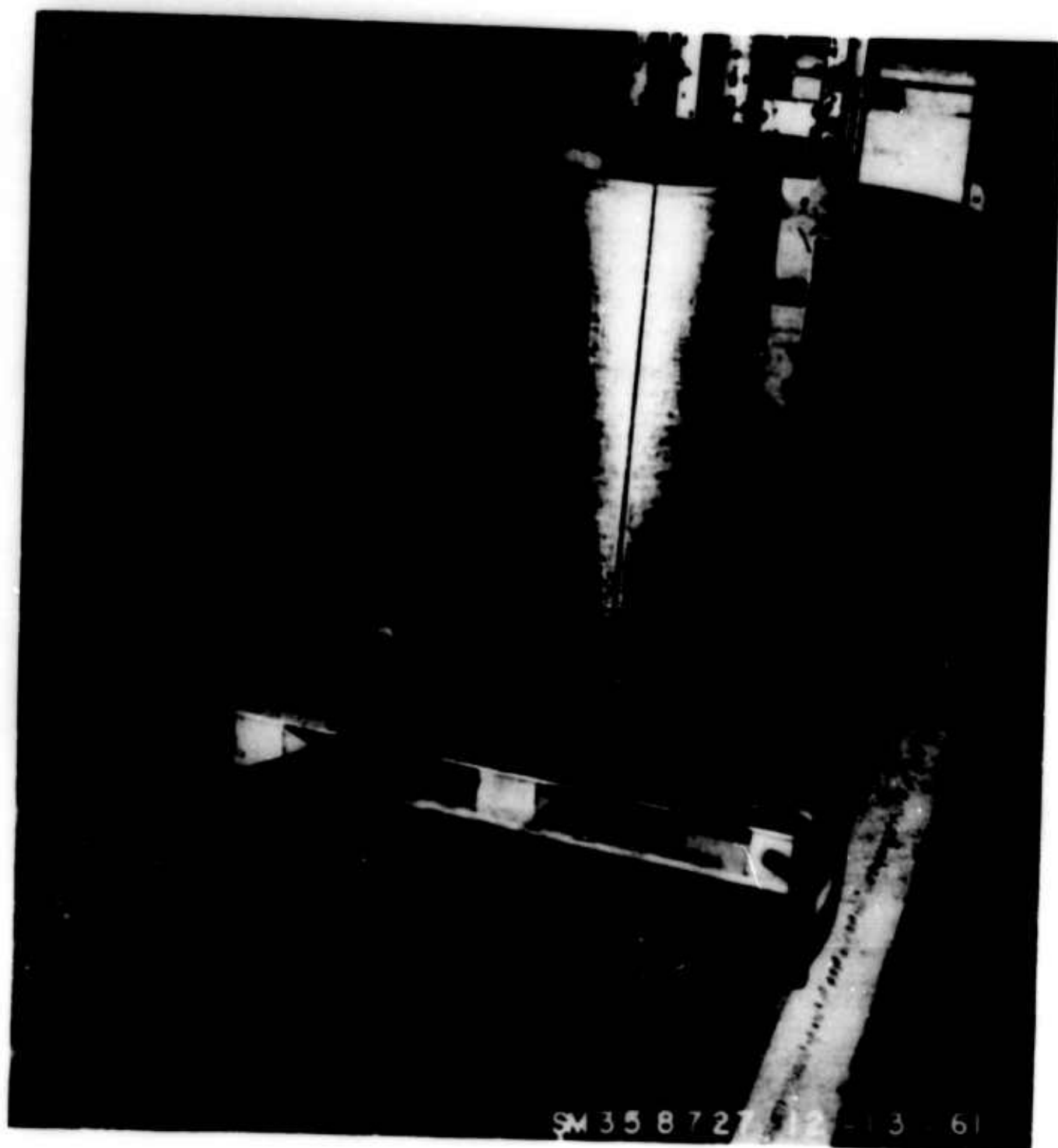


FIGURE 5

MECHANICAL SIZER FOR CYLINDERS



FIGURE 6

MECHANICAL SIZER FOR DOMES (SM 358726)



FIGURE 7

PHOTOMICROGRAPH OF Ti 6Al-4V FUSION WELD

Mag. 20 X

Kroll's Etch

(M 16375)

FIGURE 8

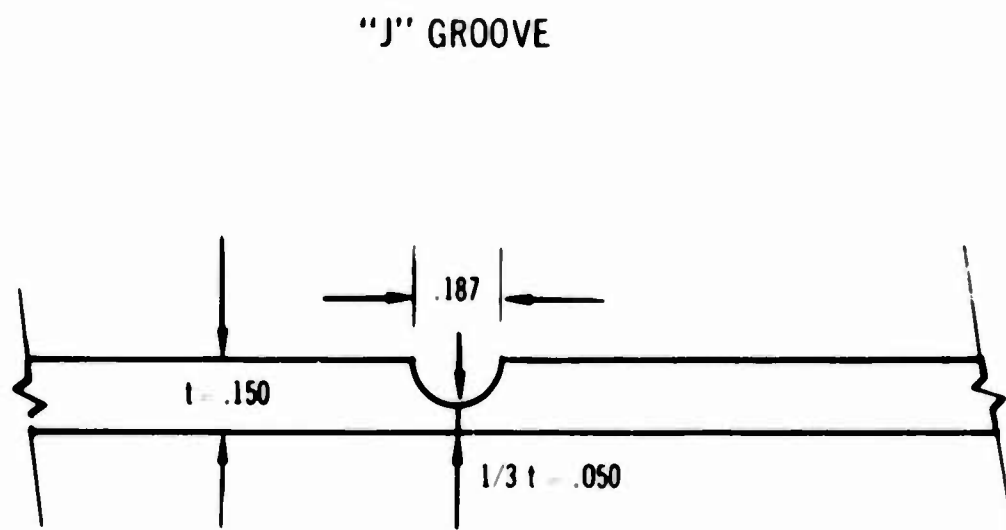


FIGURE 9

TRAIL SHIELD USED IN TIG
WELDING OF 0.150 IN FUSION BUTT

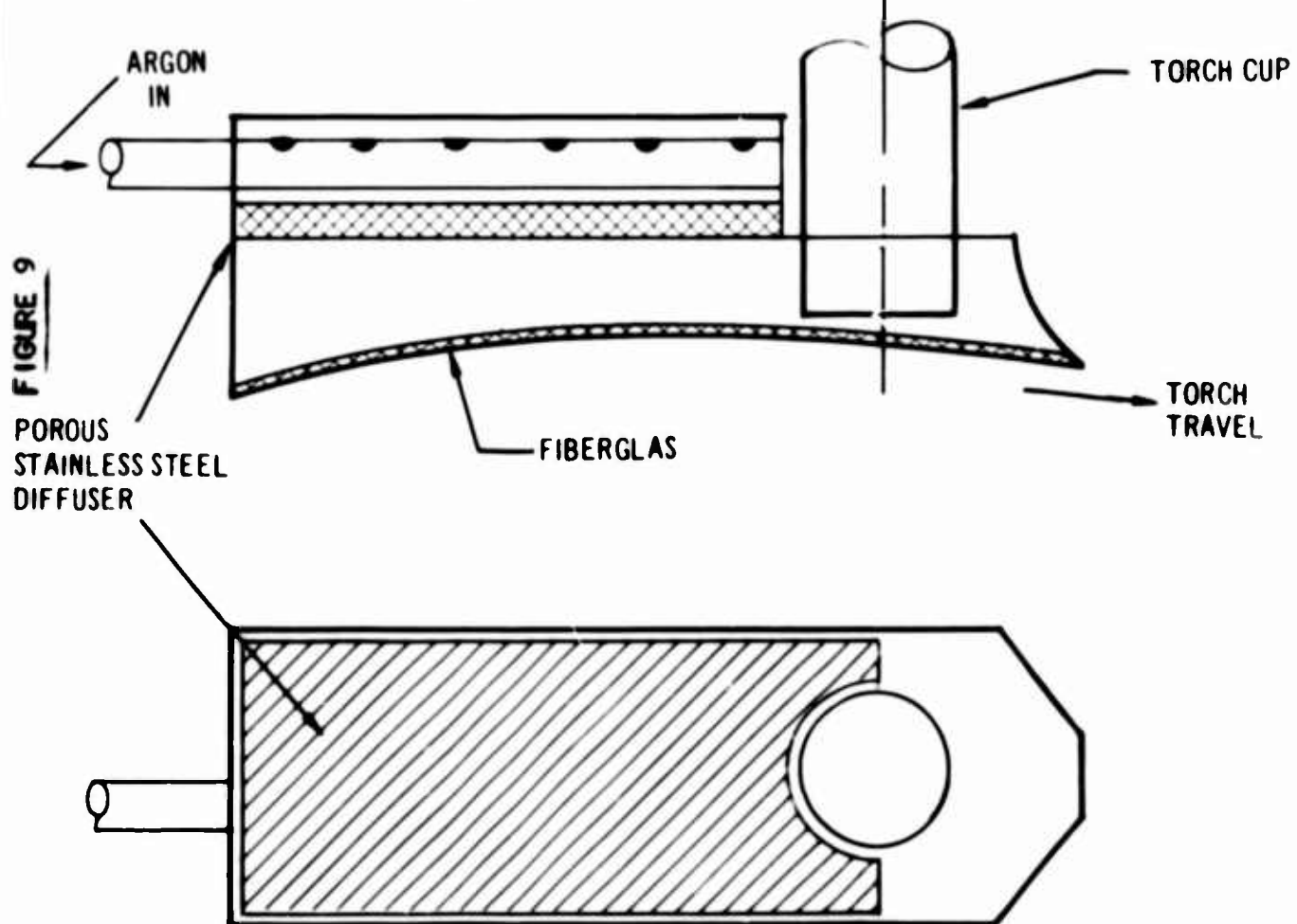
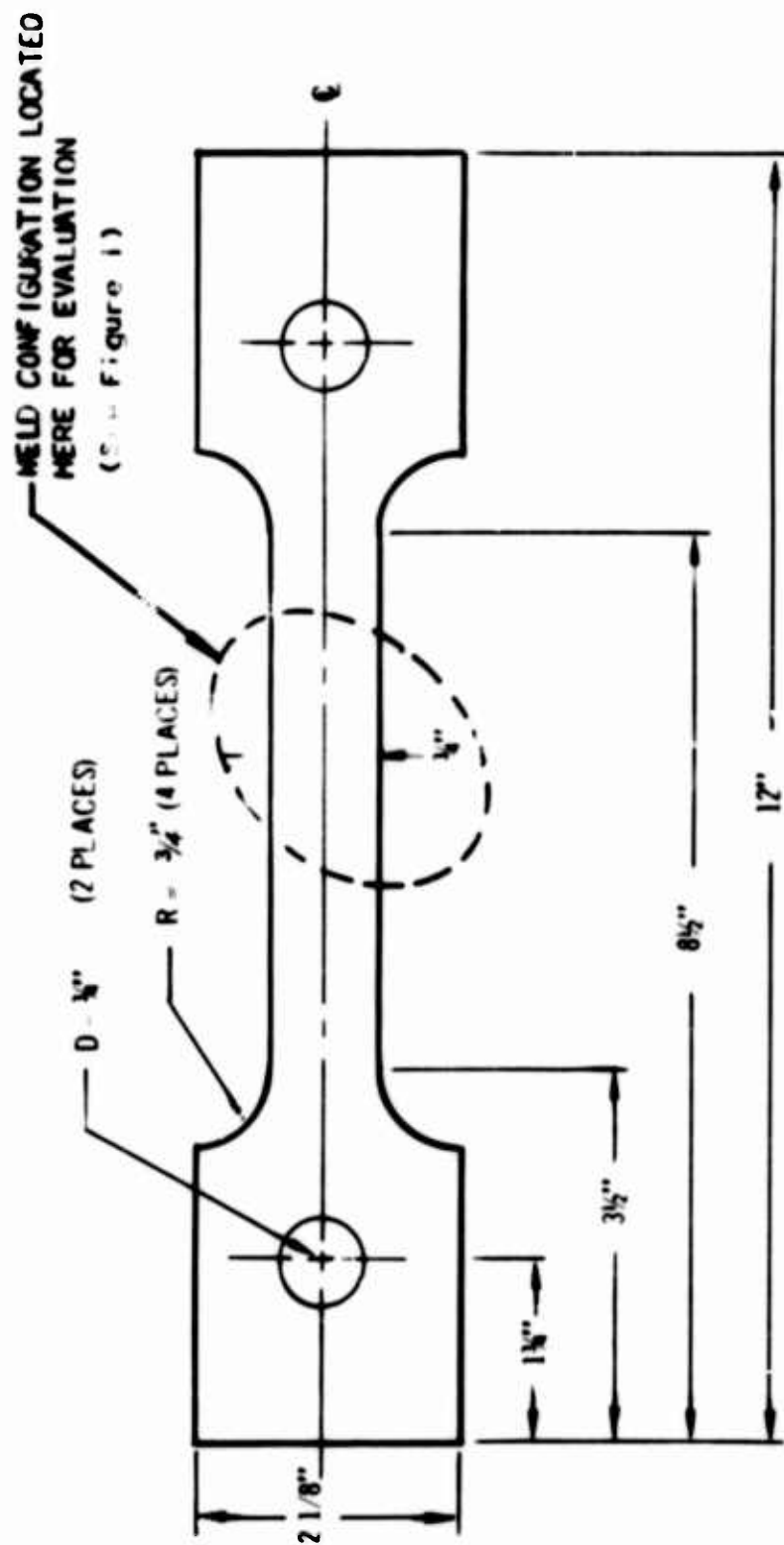


FIGURE 10**TENSILE SPECIMEN**

- NOTES:
1. FINISH IS TO BE RMS 125
 2. HOLES MUST BE ON ϕ WITHIN 0.002"

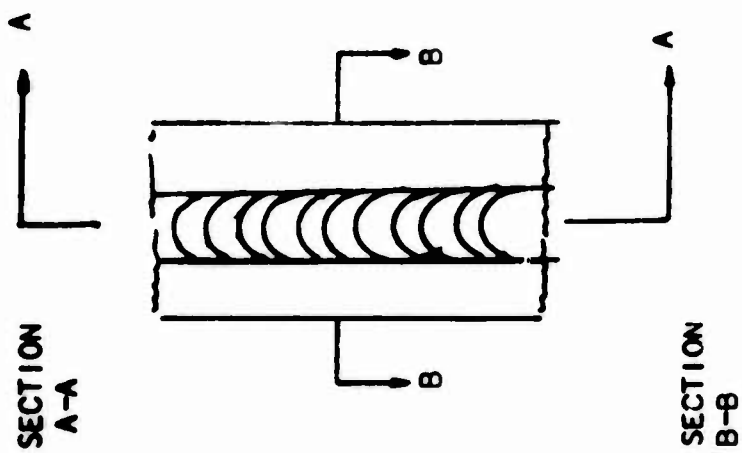


Mag. 10X

Kroil's Etch
(M 14485)

FIGURE 11

PHOTOMICROGRAPH OF RESISTANCE
LAP WELD



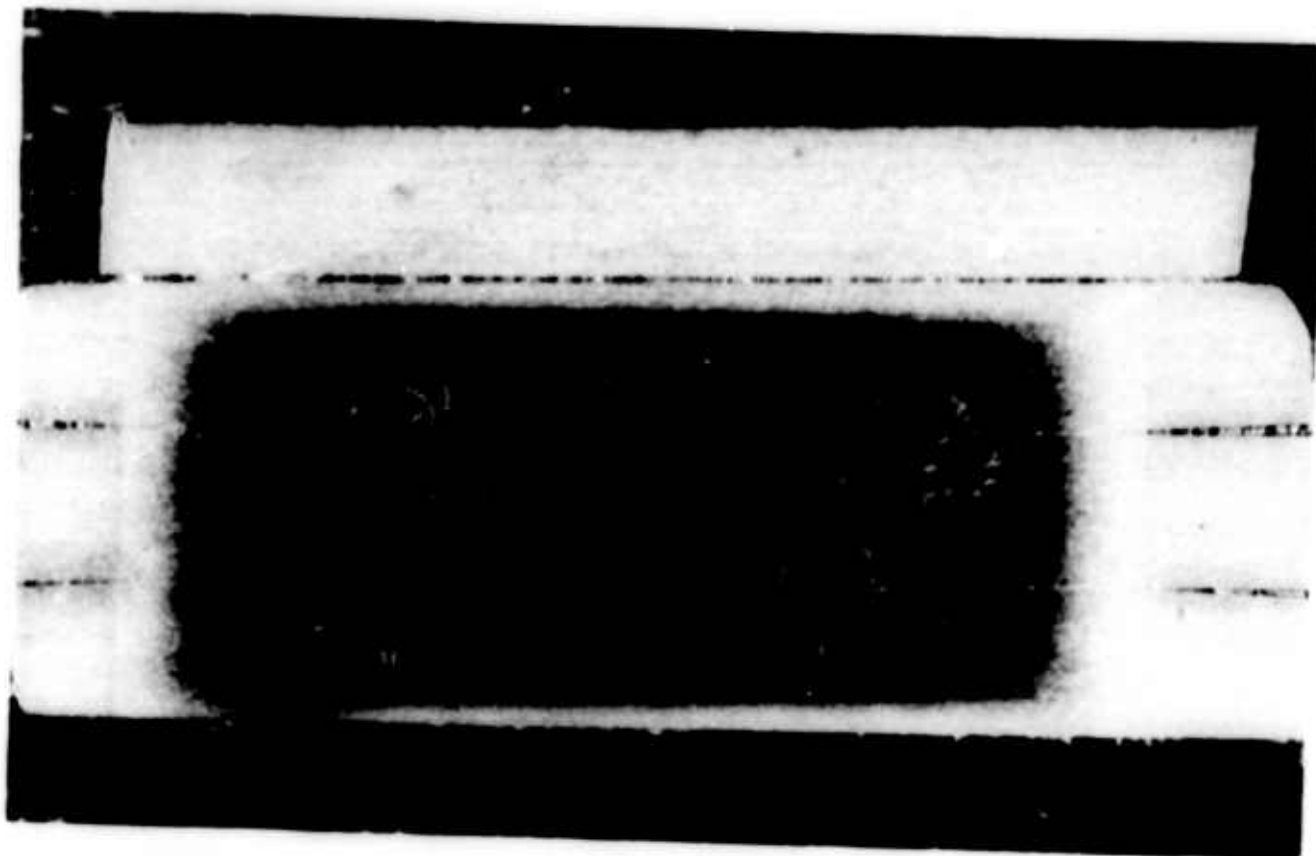


FIGURE 12

PHOTOMICROGRAPH OF RESISTANCE STRAP WELD

Mag. 10X

Kroll's Etch

(M 14449)

Note: This view corresponds to Section B-B of Figure 11.



FIGURE 13

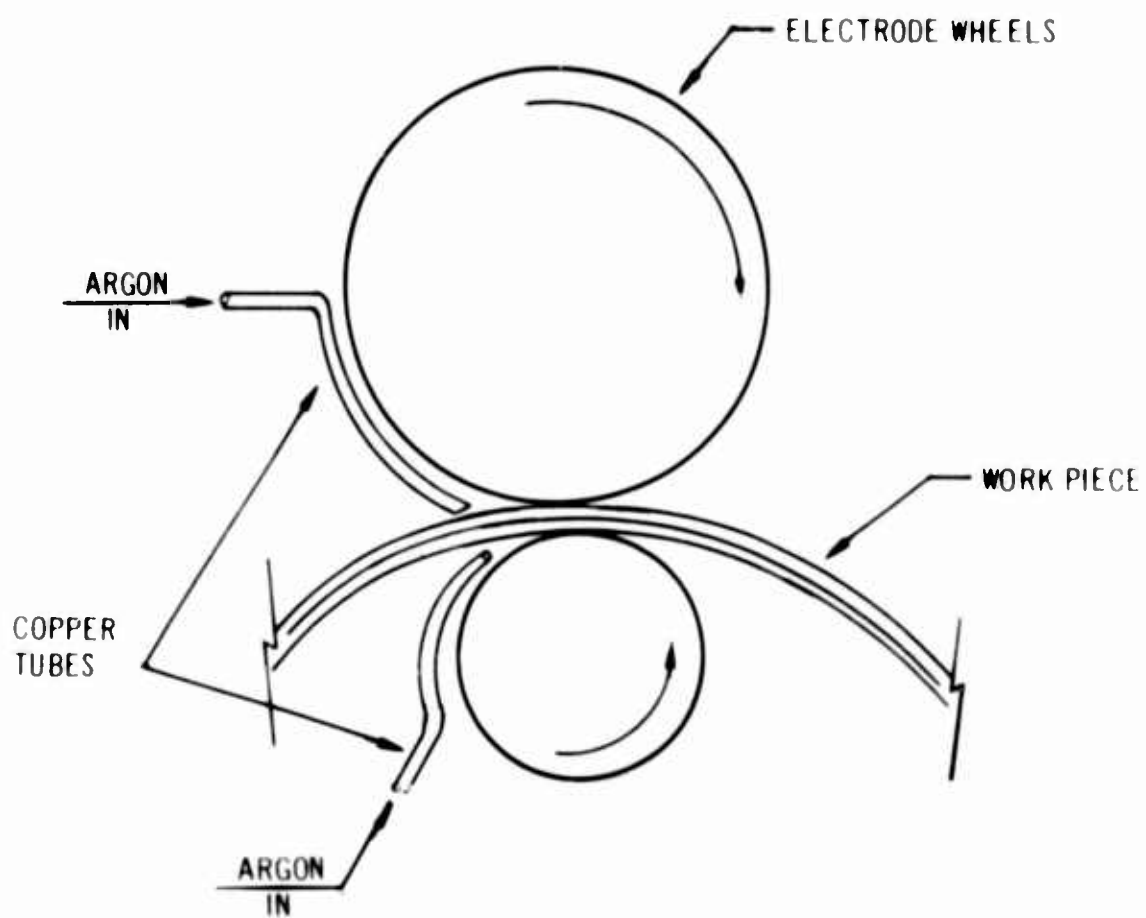
ARGON PURGE CHAMBER (SM 358730)



FIGURE 14

WELD FIXTURE FOR CIRCUMFERENTIAL FUSION WELD

FIGURE 15



ARGON SHIELDING FOR RESISTANCE WELDS

FIGURE 16

CUT-AWAY VIEW OF A TITANIUM CYLINDER
(SHOWING ARRANGEMENT AND LOCATION OF SHIELDING
ENVELOPE USED FOR CLOSURE WELD)

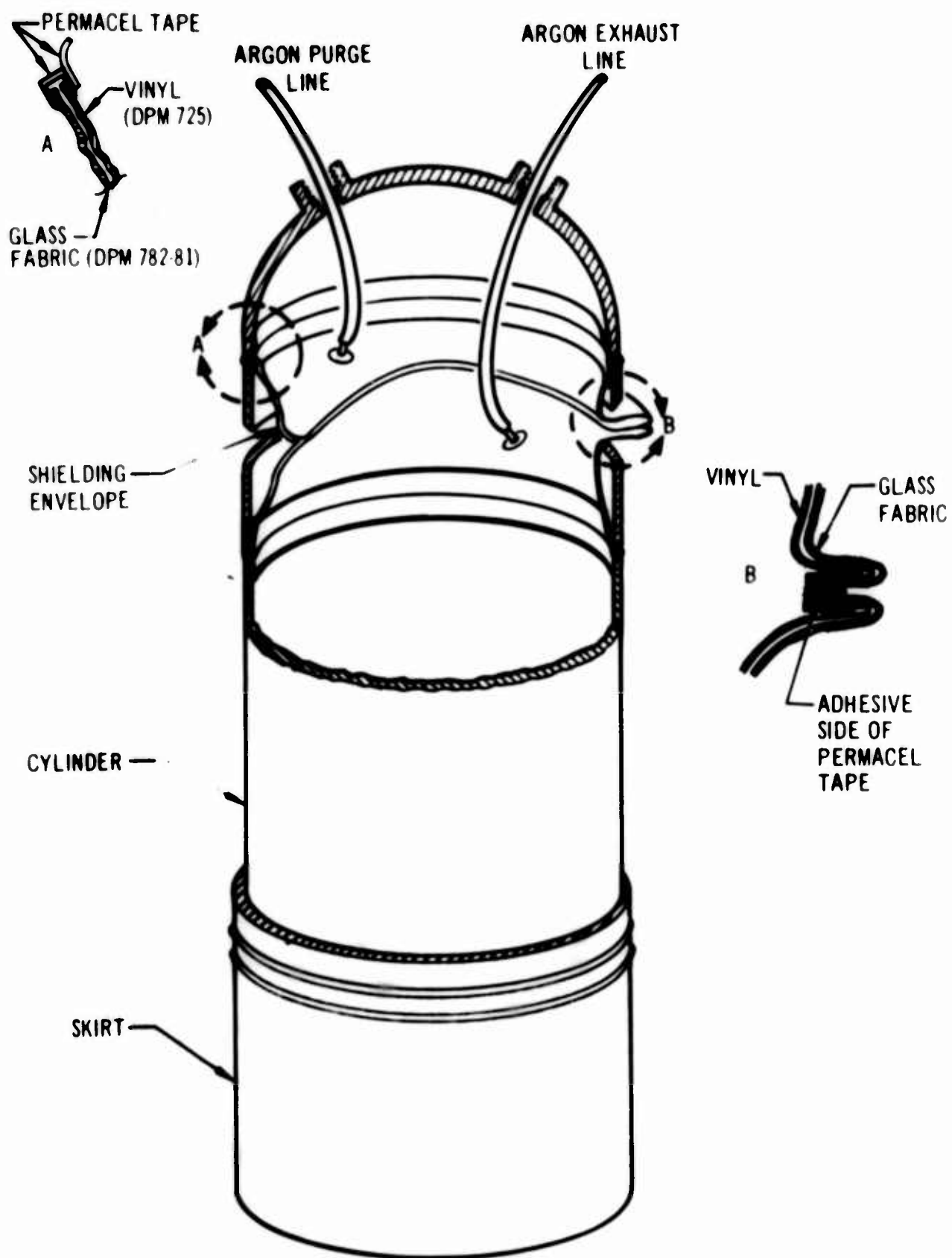


FIGURE 17

TITANIUM TANK FOR AMBIENT TEMPERATURE

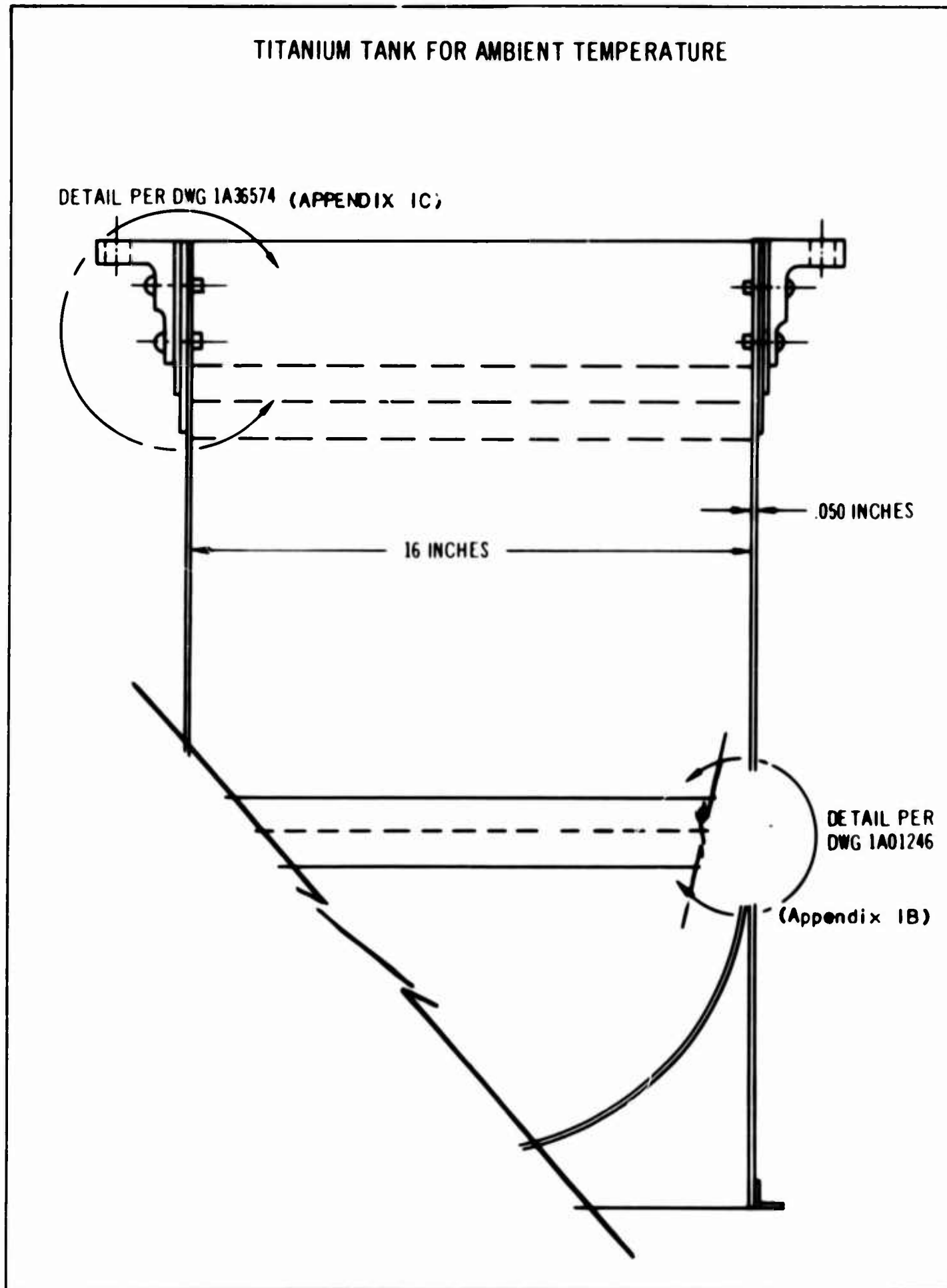


FIGURE 18

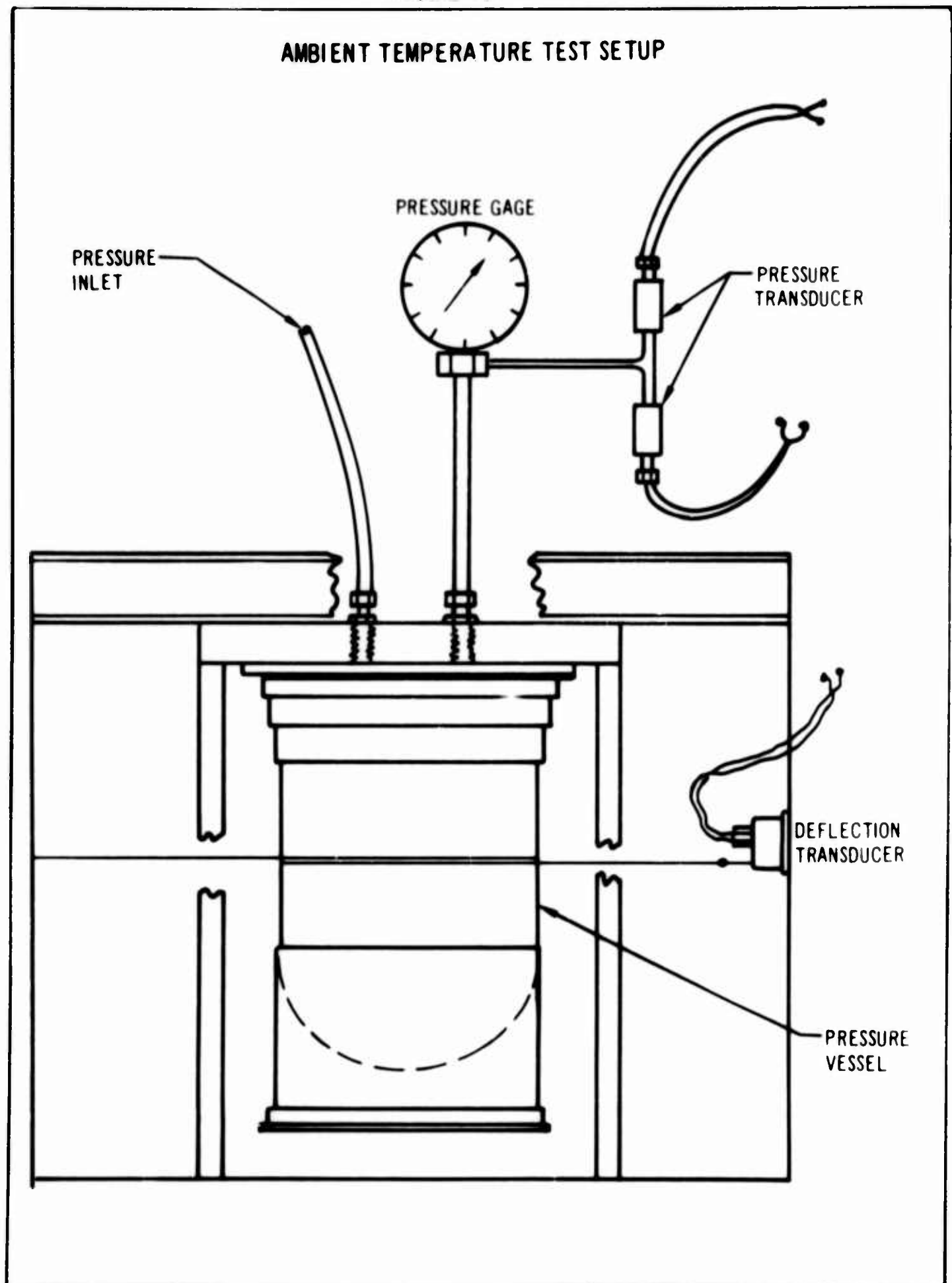
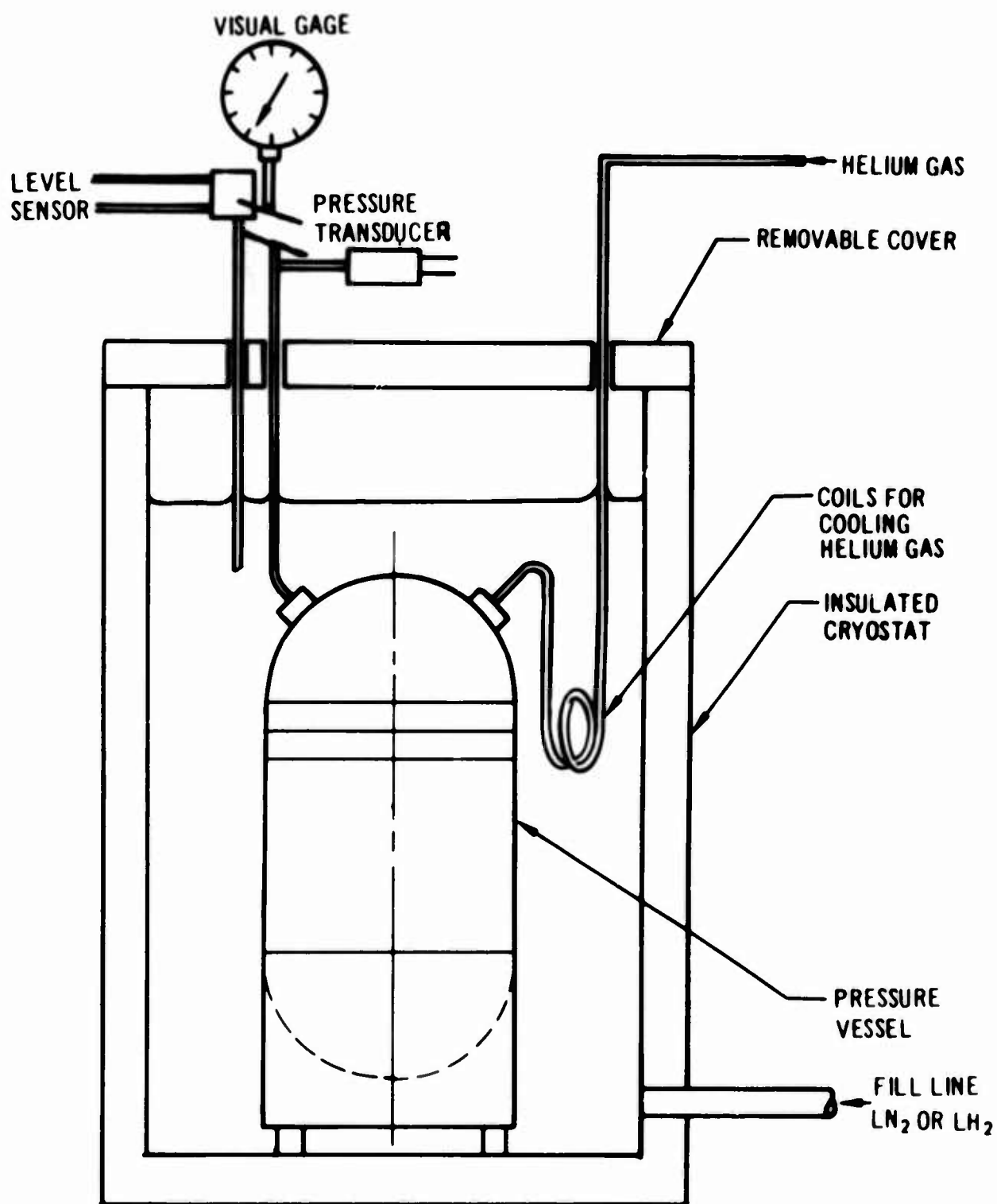


FIGURE 19

TYPICAL CRYOGENIC TEST SETUP



NOTE: For burst test at -80°F (-62°C), the outside of pressure vessel was packed with dry ice. No liquid-dry ice mixture was used.

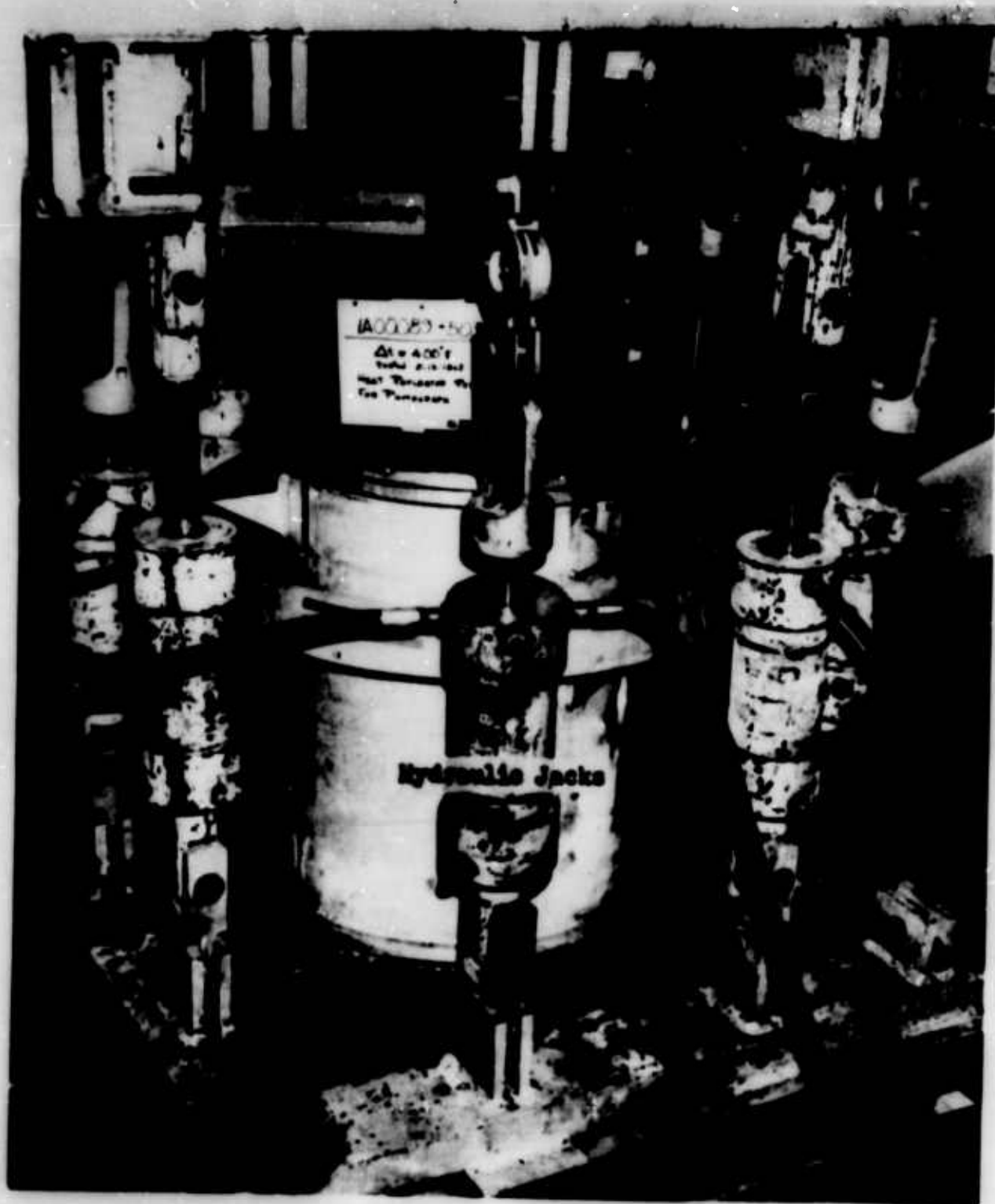


FIGURE 20

COMPRESSION TEST SETUP FOR 30-INCH CYLINDER (SM 354175)

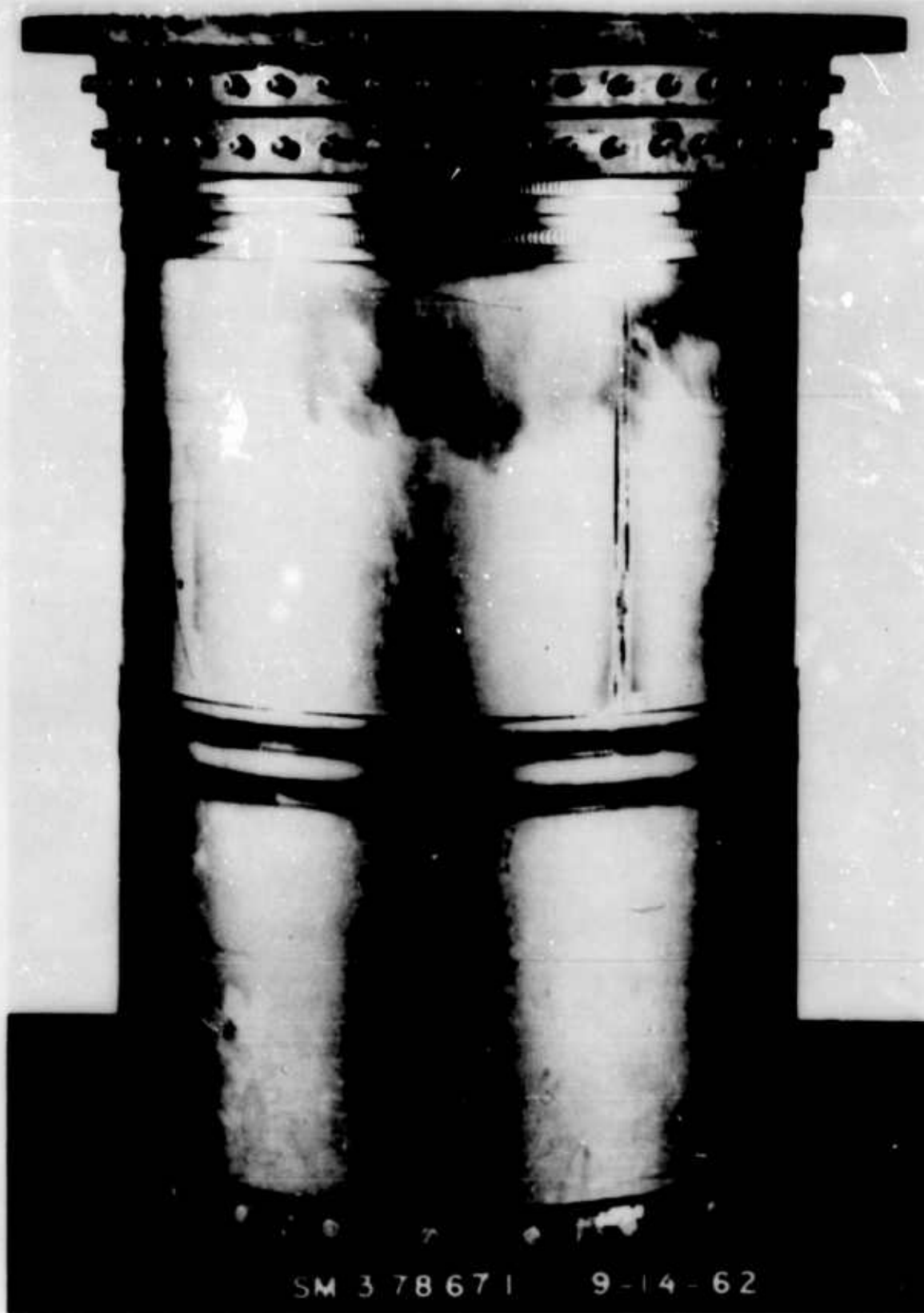


FIGURE 21

PRESSURE VESSEL Ti-1 (OR Ti-2) BEFORE BURST TEST

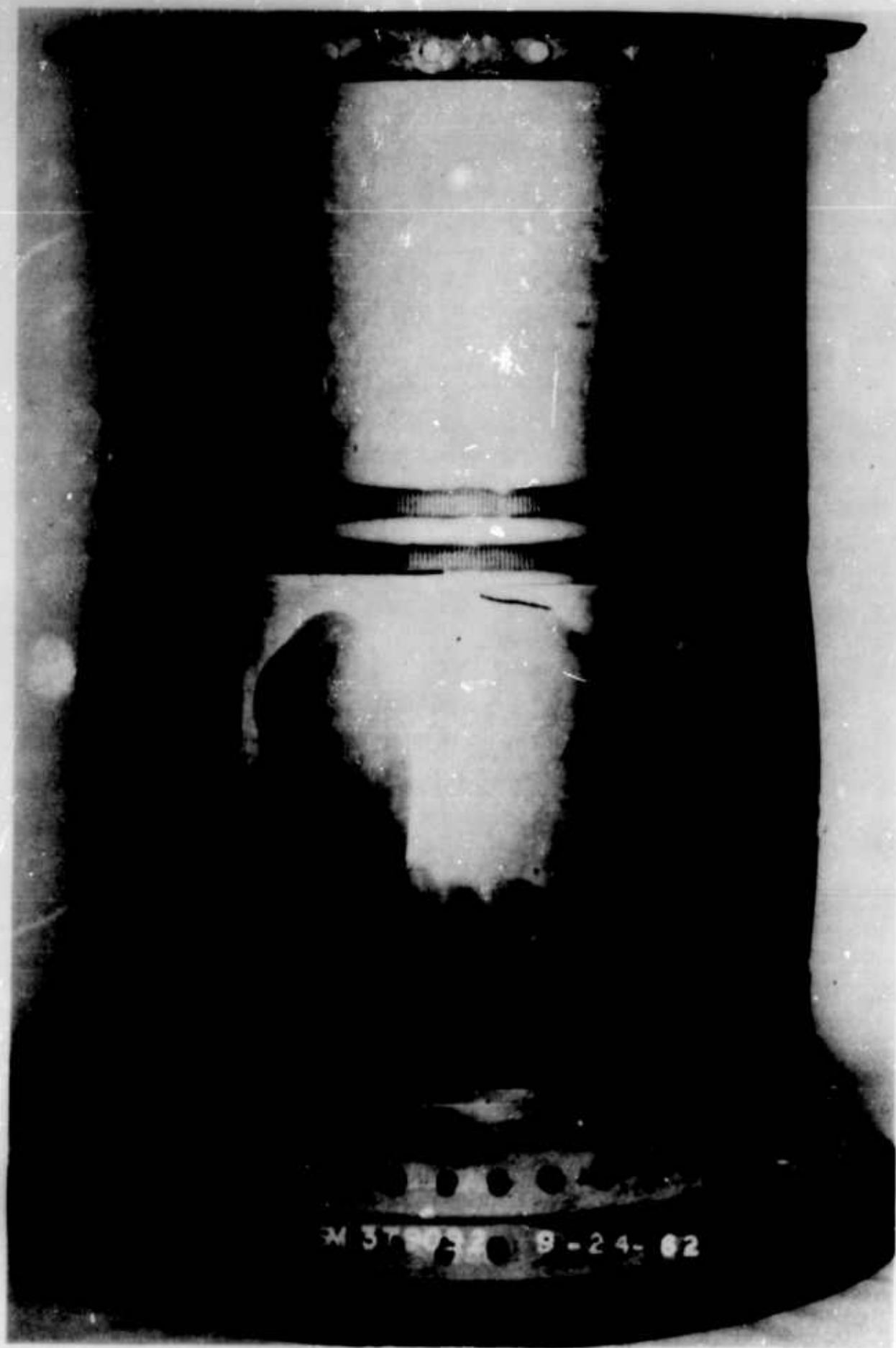


FIGURE 22

PRESSURE VESSEL TI-2 AFTER BURST TEST AT ROOM TEMPERATURE



FIGURE 23

PRESSURE VESSEL Ti-3 (c. Ti-4) BEFORE BURST TEST



FIGURE 24

PRESSURE VESSEL Ti-3 AFTER BURST TEST AT -80°F (-62°C)



SM 38-049

FIGURE 25

PRESSURE VESSEL Ti-1A (or 2A) BEFORE BURST TEST

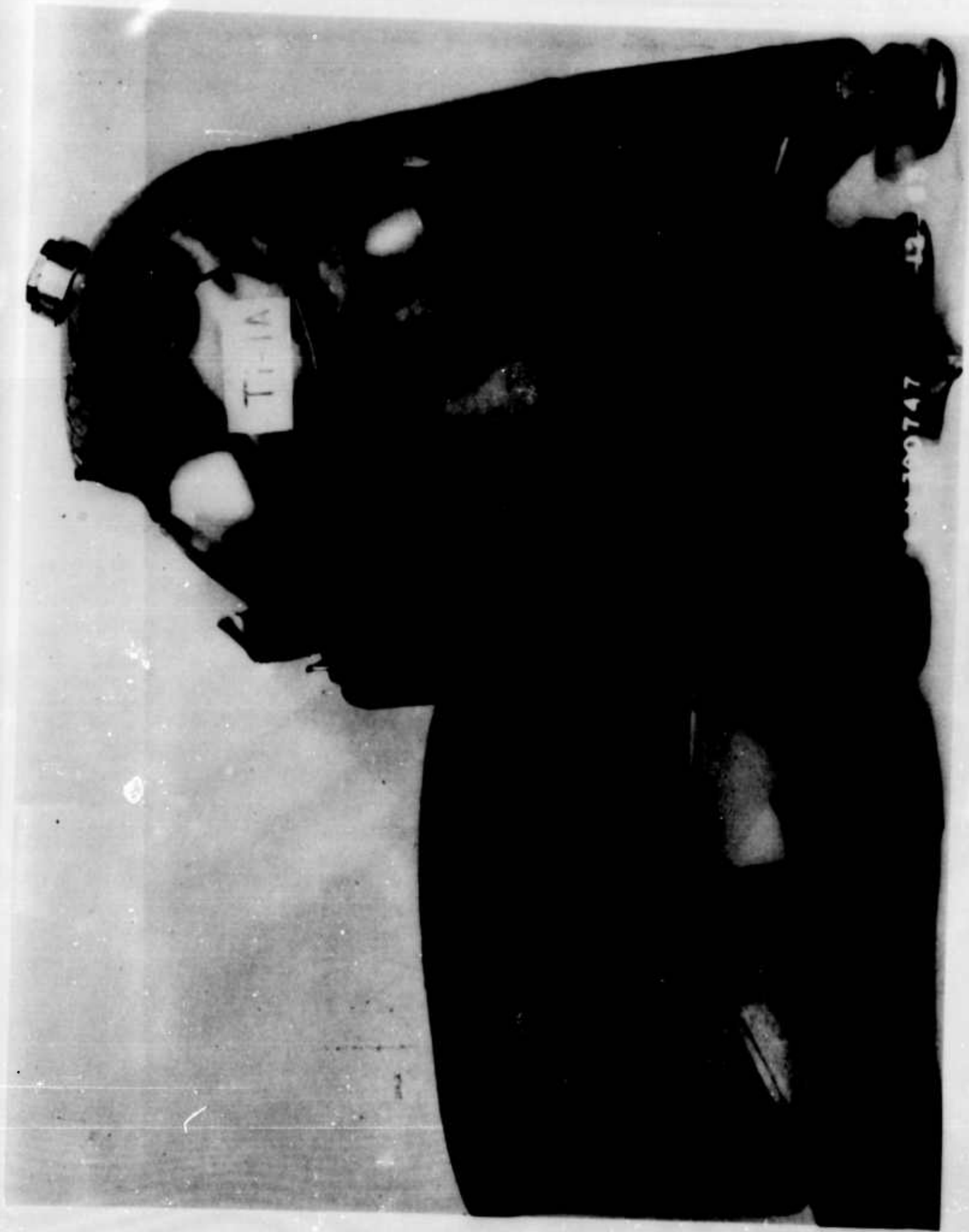


FIGURE 26

PRESSURE VESSEL Ti-1A AFTER BURST TEST AT -320°F (-196°C)

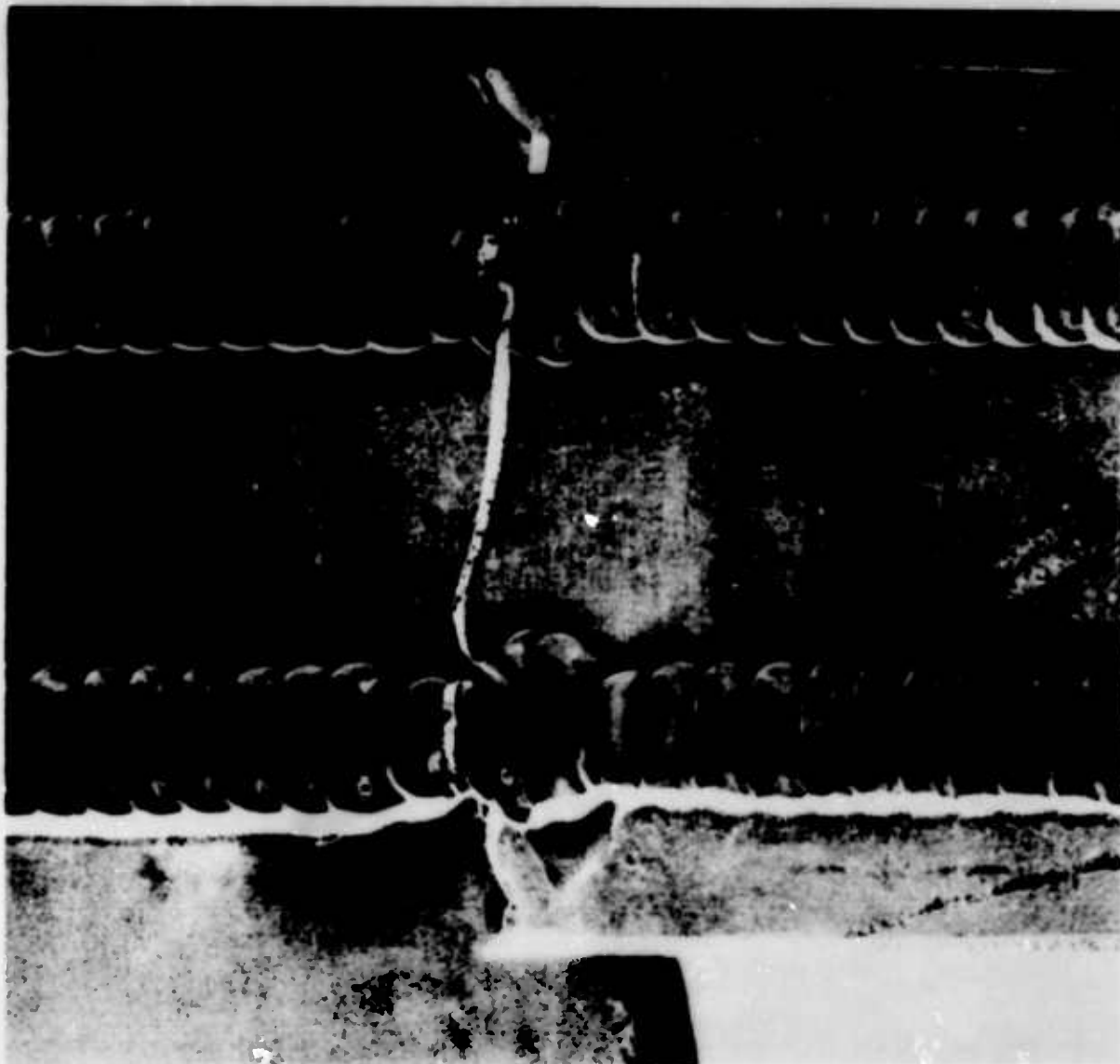


FIGURE 27

UNDERSIZE NUGGET IN PRESSURE VESSEL TI-1A WHICH FAILED PREMATURELY AT
-320°F (-196° C)

Mag. 2X

(M 16867)

PREPARED BY: _____

PAGE: _____

CHECKED BY: _____

DIVISION _____

MODEL: _____

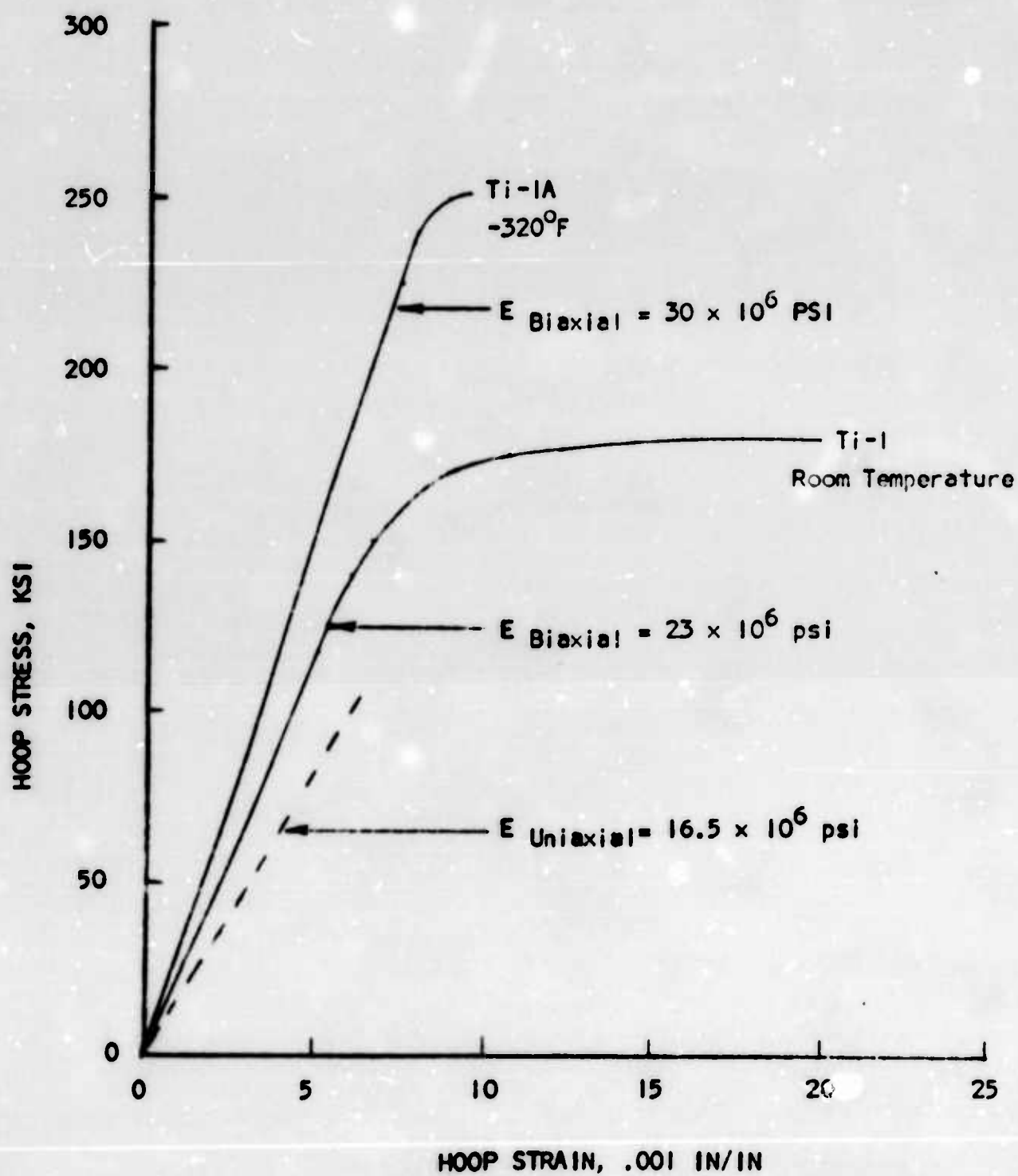
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TITLE: _____

REPORT NO: _____

FIGURE 28

HOOP STRESS-STRAIN CURVES FOR Ti-1 AND Ti-1A



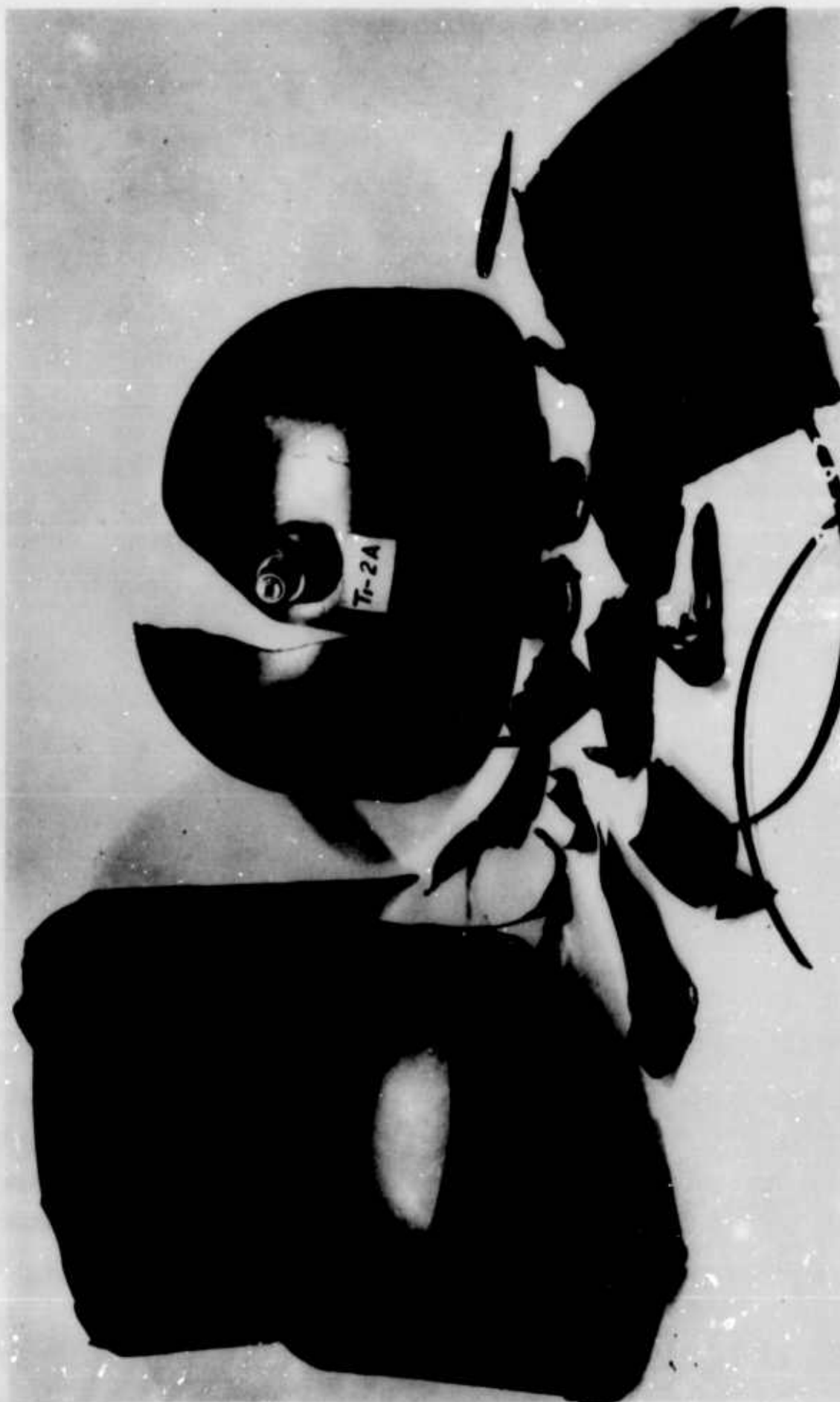


FIGURE 29

PRESSURE VESSEL Ti-2A AFTER BURST TEST AT -320°F (-196°C)

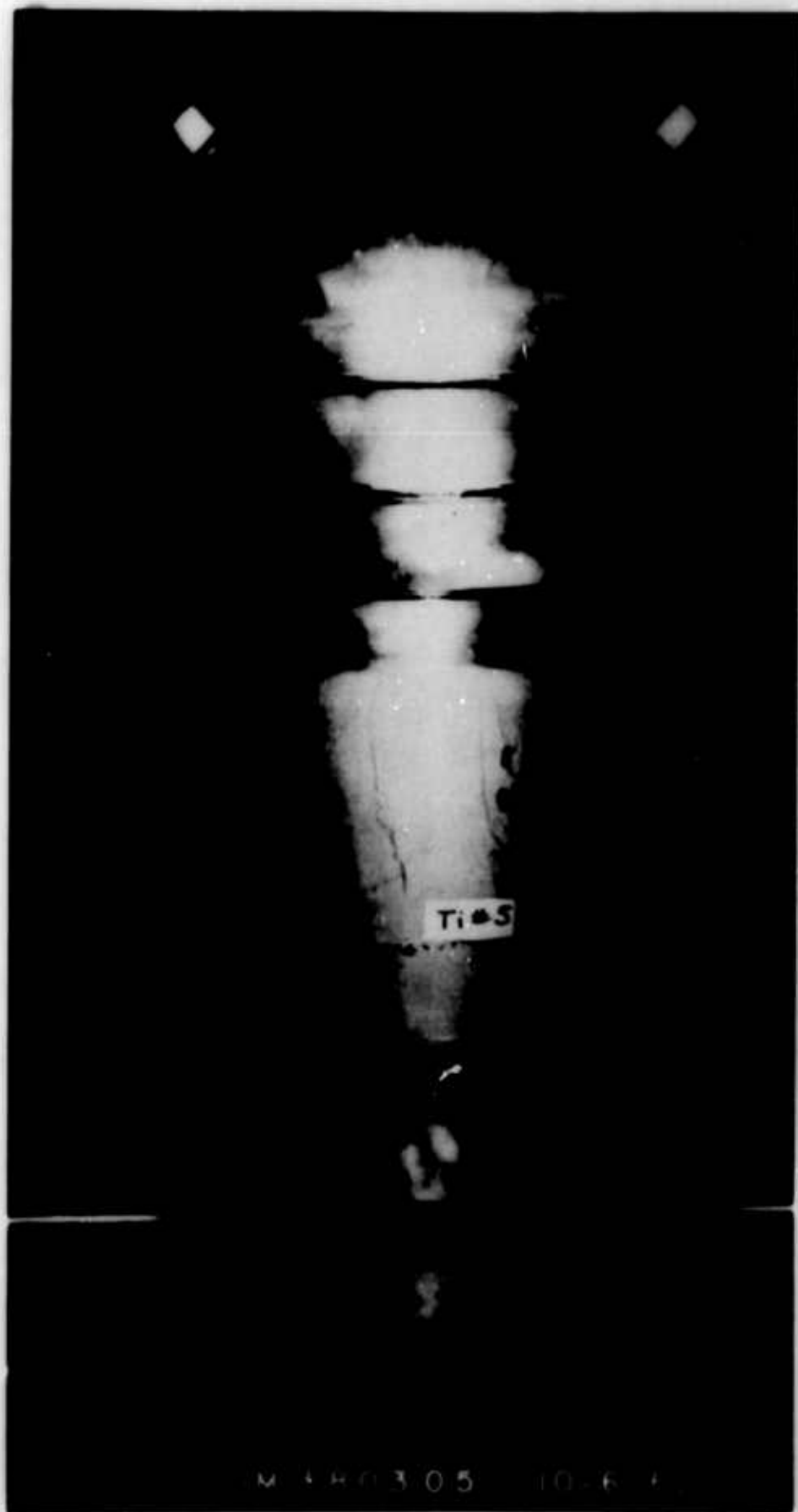


FIGURE 30.

PRESSURE VESSEL Ti-5 (or Ti-6) BEFORE BURST TEST

M 480305 10-6 F



FIGURE 31

PRESSURE VESSEL Ti-5 AFTER BURST TEST AT -423°F (-253°C)



FIGURE 32

PRESSURE VESSEL Ti-4 AFTER BURST TEST AT -423°F (-253°C)

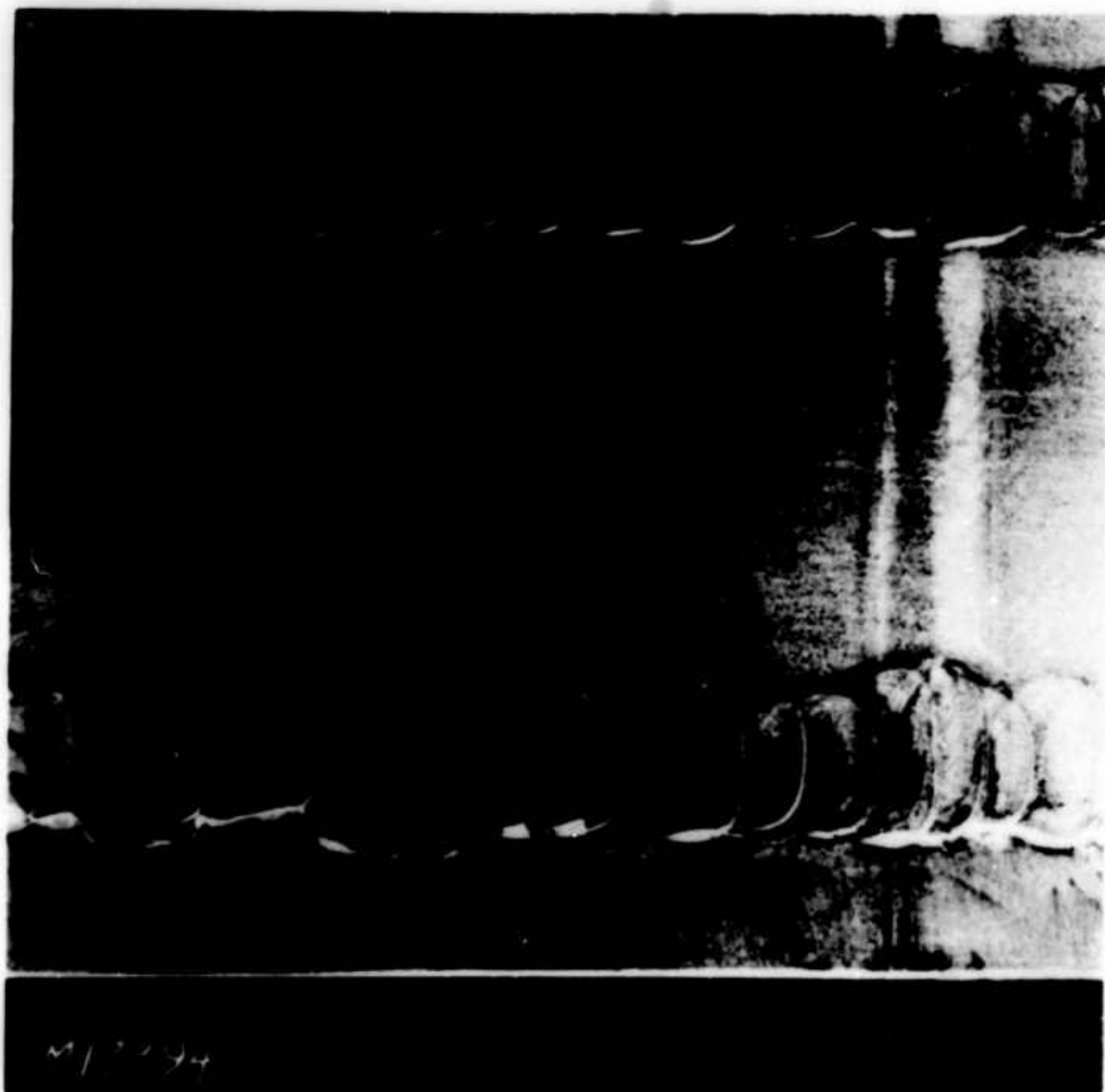


FIGURE 33

PHOTOGRAPH OF THE PROBABLE ORIGIN OF FAILURE (INDICATED BY AN ARROW).
NOTE THE OVERLAP OF START-STOP POINT.

Mag 2-1/2 X

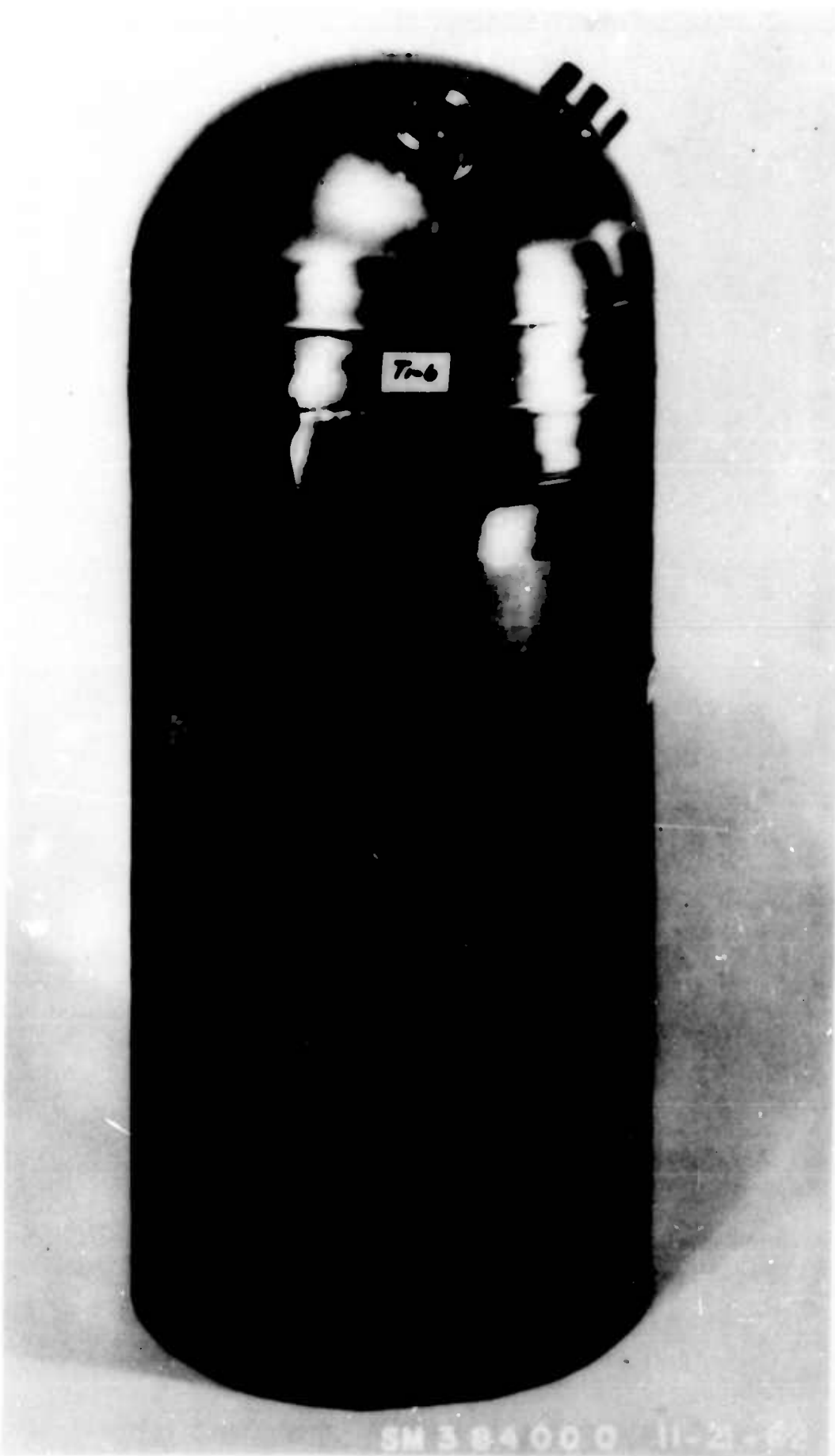


FIGURE 34

PRESSURE VESSEL Ti-6 FAILED DURING PROOF TESTING AT ROOM TEMPERATURE

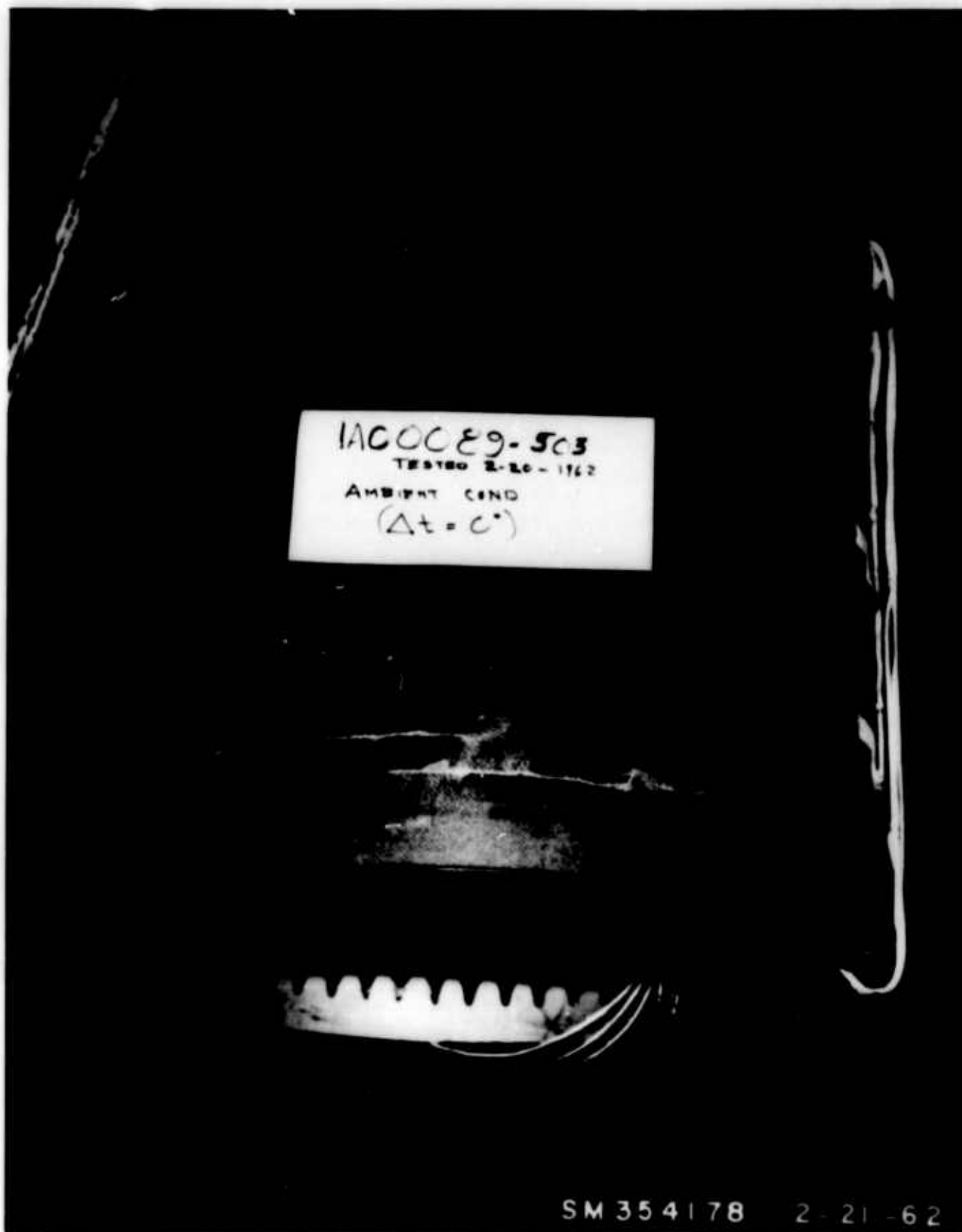
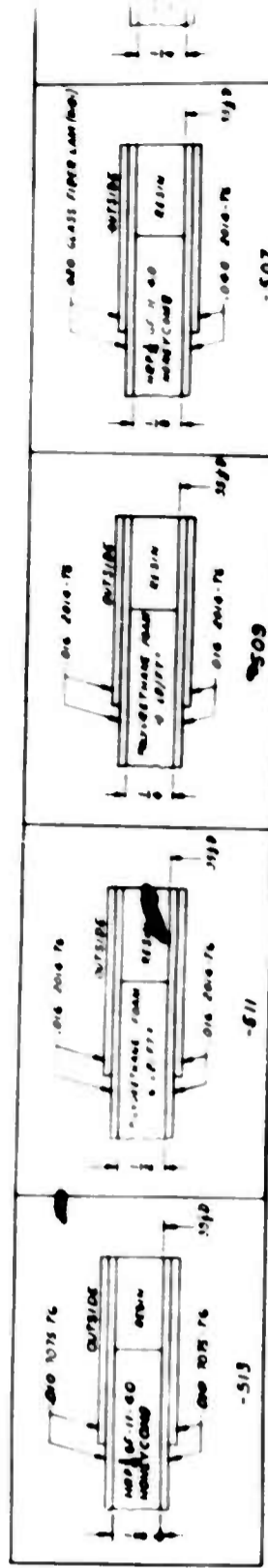
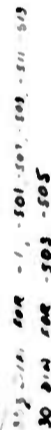
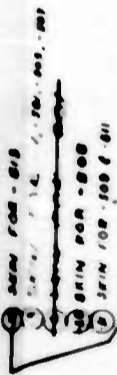


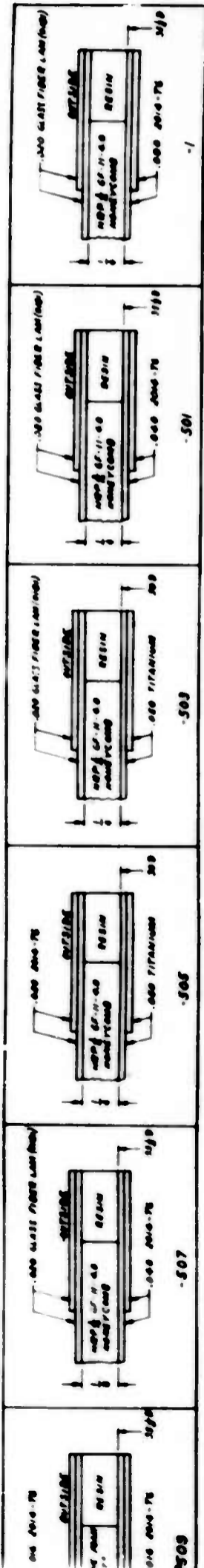
FIGURE 35

SANDWICH CYLINDER AFTER COMPRESSION TEST AT ROOM TEMPERATURE



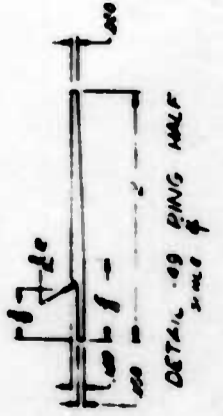
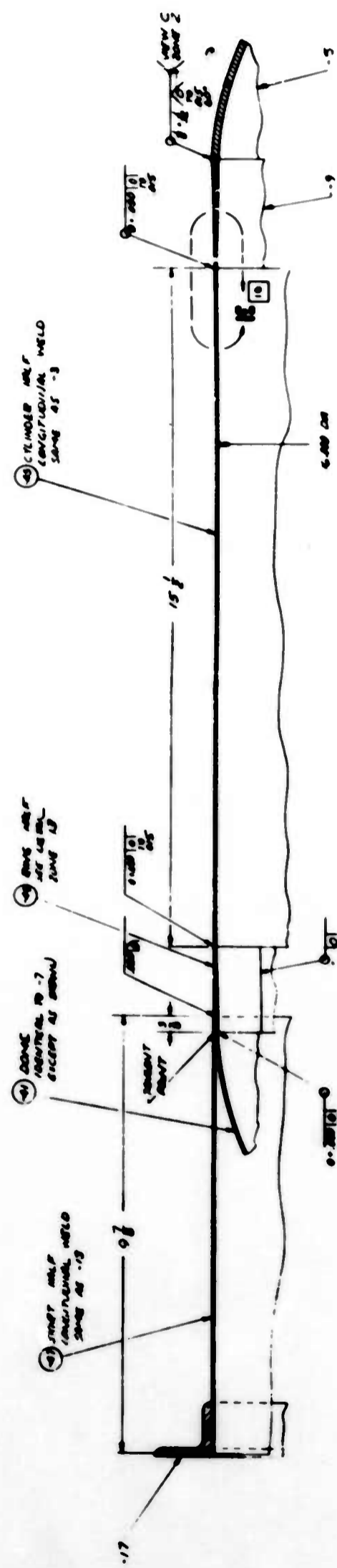
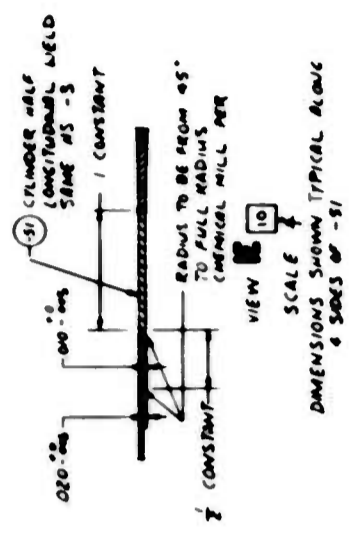
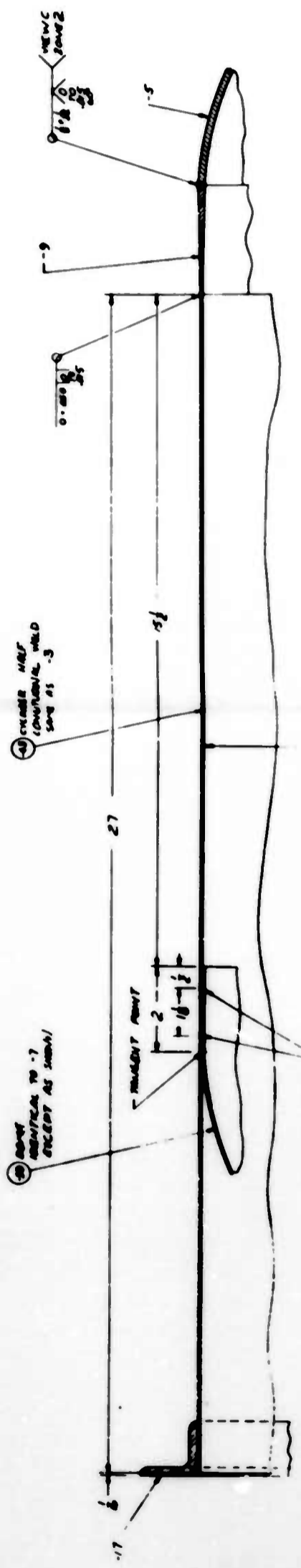
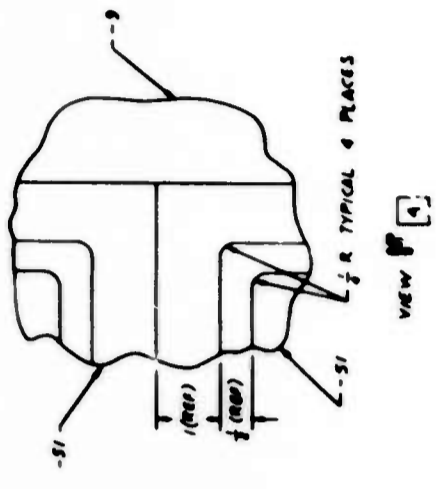
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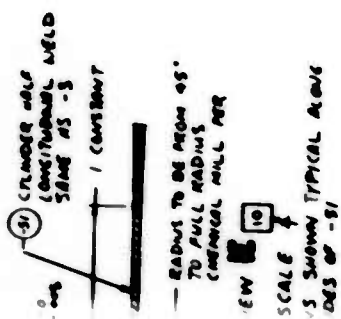
THESE DIAGRAMS ARE FOR
ENGINEERING REFERENCE ONLY



Ericksen, Barbara

WINTERCOM
TUNING, TUNING
AND CONNECTION

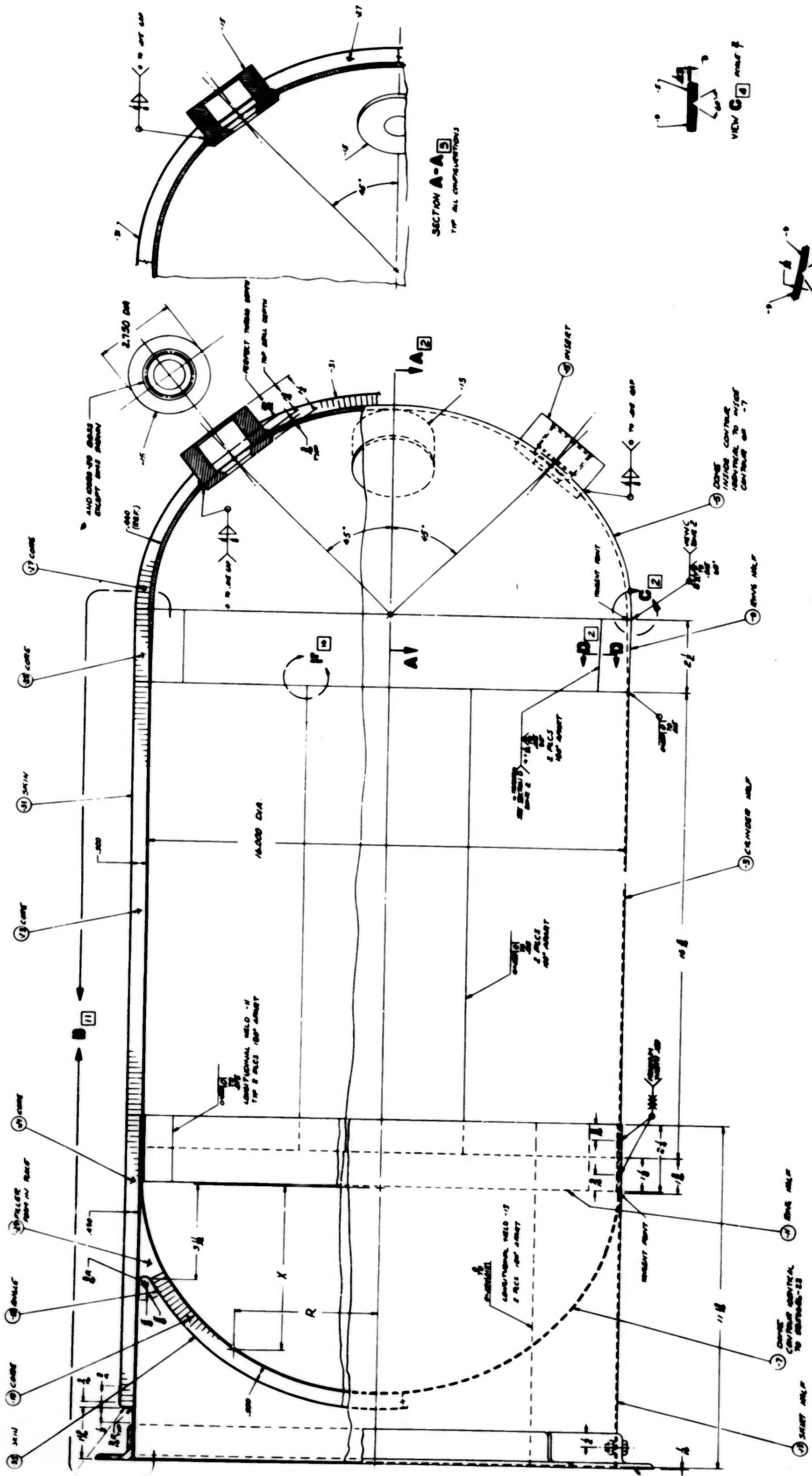




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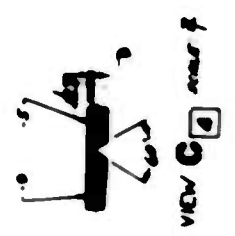


C

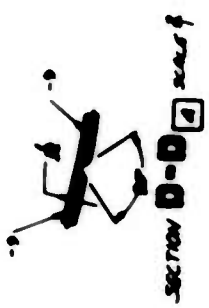


- GENERAL
UNLESS OTHERWISE SPECIFIED
1. ALL DIMENSIONS IN INCHES
 2. HOLE SYMBOLS IN
 3. HOLE AND RECESS
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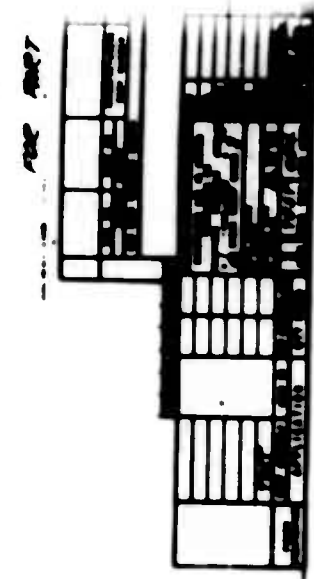
SECTION A-A
TYP. ALL DIMENSIONS



VIEW C-D

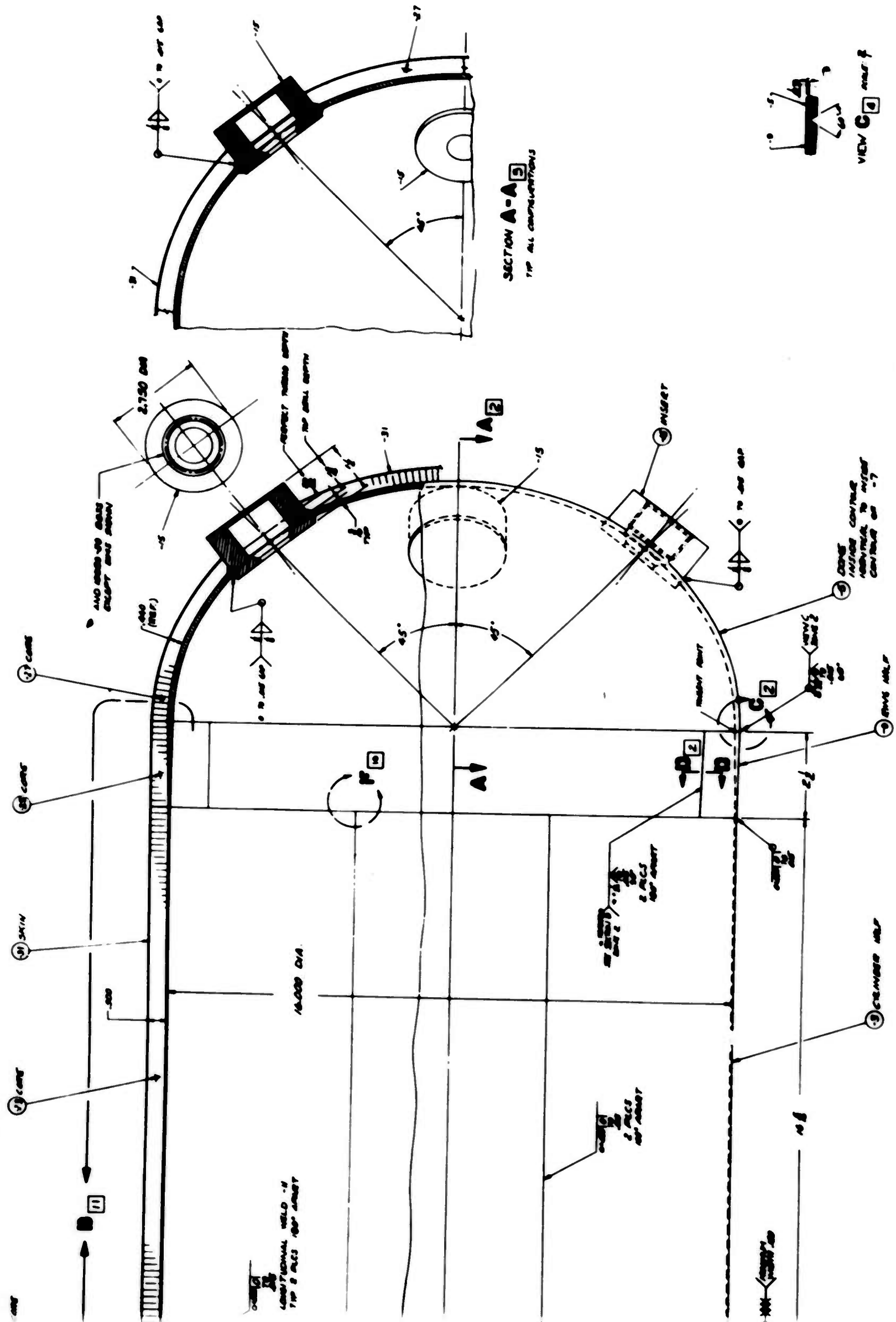


SECTION D-D

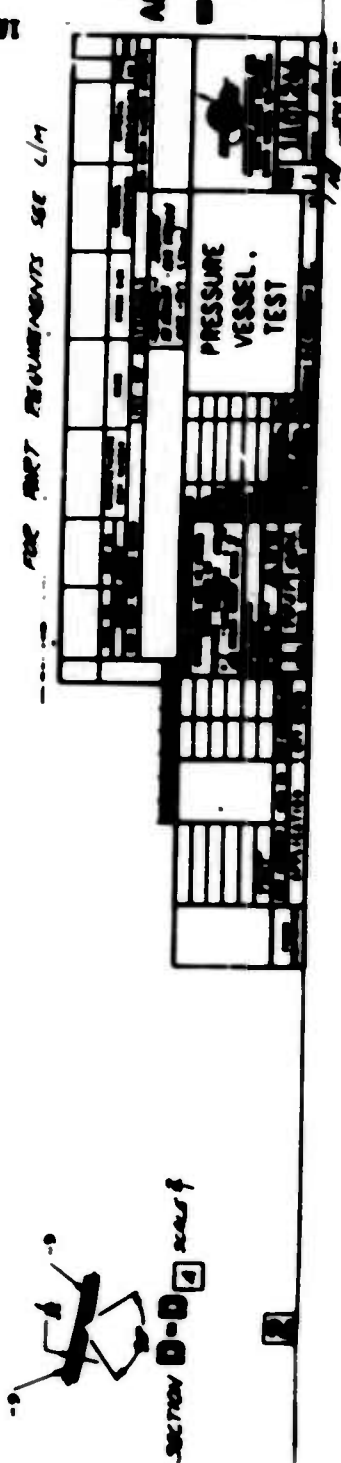


SECTION E-E

D



GENERAL NOTES
 UNLESS OTHERWISE SPECIFIED
 1. ALL DIMENSIONS SHALL BE IN INCHES
 2. WELD SYMBOLS ARE AS SHOWN
 3. WELD METAL SHALL BE AS SHOWN
 4. CONSTRUCTION WELDS OF MATERIALS MUST BE AT LEAST 1/8" THICK
 5. CONSTRUCTION WELDS SHALL BE NECESSARY TO FACILITATE ASSEMBLY
 6. DIMENSIONS TO CENTER LINE
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APPENDIX B

CHEMICAL COMPOSITIONS AND REPORTED MILL ANNEAL CONDITIONS OF EXPERIMENTAL SHEET MATERIALS

HEAT NO.	MAT'L DESCRIPTION	TEST	YIELD STRENGTH PSI	ULTIMATE STRENGTH PSI	E LONG. (2 IN.)	MAT'L DIMENSIONS	NO. PCS	CHEMICAL ANALYSIS								
								C	F _o	N ₂	Al	Vo	H ₂	Sn	Mn	Ti
D-955	6A1-4V	L	139,400	146,300	12.5	.050X30X60	1	.026	.11	.014	6.0	4.0	.006	--	--	Rem
D-1414	6A1-4V	T	130,000	138,400	13.5	.050X30X60	1	.021	.12	.019	5.9	4.0	.006	--	--	Rem
		L	137,200	144,700	13.5											
D-755	6A1-4V	T	100,900	147,000	13.5	.050X30X60	2	.028	.09	.016	5.9	4.1	.006	--	--	Rem
		L	159,800	145,000	13.0											
M-9010	6A1-4V	T	134,100	141,000	12.5	.050X36X96	1	.024	.12	.020	6.0	4.0	.006	--	--	Rem
		L	142,200	150,200	13.0											
M-8159	6A1-4V	T	130,400	142,600	12.0	.050X30X60	2	.018	.09	.010	5.8	4.1	.007	--	--	Rem
		L	134,400	143,500	12.0											
M-8161	6A1-4V	T	130,000	141,300	12.5	.050X30X30	2	.023	.11	.014	5.7	4.0	.006	--	--	Rem
		L	135,600	141,200	10.5											
D-1456	6A1-4V	T	134,400	143,500	12.0	.050X36X120	4	.020	.13	.019	6.1	4.0	.006	--	--	Rem
		L	31,300	52,700	35.0											
D-1755	Ti-55A	T	33,900	50,000	34.0	.150X30X30	3	.025	.06	.014	--	--	.003	--	--	Rem
		L	49,900	71,000	27.0											
D-1762	Ti-55A	T	55,000	69,700	28.0	.150X30X30	2	.025	.09	.016	--	--	.005	--	--	Rem
		L	140,000	146,400	13.5											
M-9956	6A1-4V	T	47,000	68,000	29.0	.150X30X60	3	.027	.08	.015	--	--	.002	--	--	Rem
		L	50,000	67,400	27.5											
D-744	Ti-55A	T	64,200	83,900	27.0	.150X30X30	1	.026	.014	.023	--	--	.005	--	--	Rem
		L	68,500	83,100	27.0											
D-1576	Ti-65A	T														
D-1835	5A1-2.5Sn	T				.050X30X30	2	.026	.34	.023	5.1	--	.009	2.4	.006	Rem

L - Denotes Longitudinal Direction

T - Denotes Transverse Direction

Material procured from Titanium Metals Corporation of America

APPENDIX 2A

DEFLECTION GAUGE CALIBRATION DATA

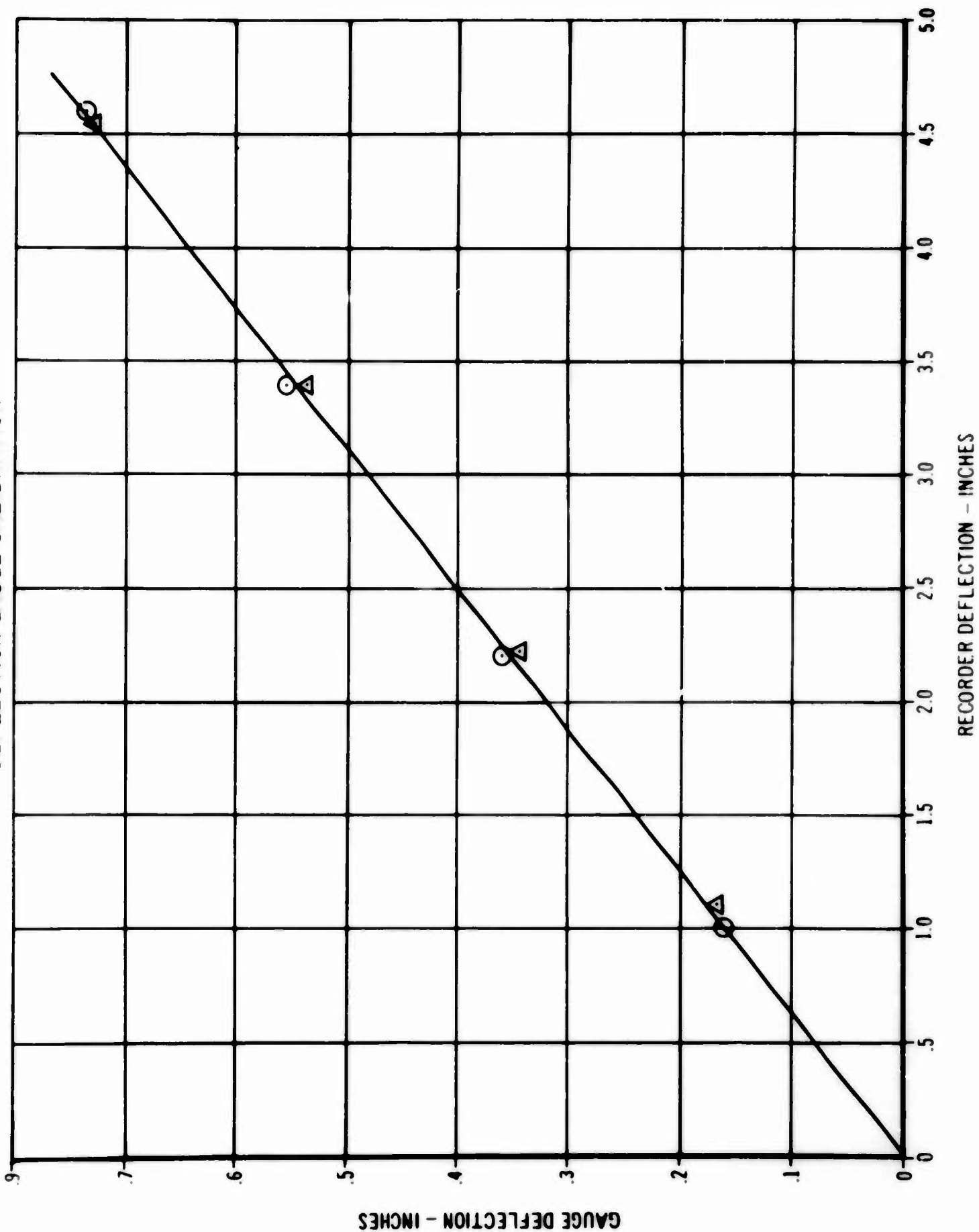
POINT NO	*ACTUAL DEFLECTION INCHES	**RECORDER DEFLECTION INCHES
1	0	0
2	.160	.99
3	.360	2.21
4	.554	3.39
5	.734	4.59
6	.898	5.67
7	.730	4.54
8	.538	3.39
9	.352	2.22
10	.165	1.09
11	0	.02
12	0	0
13	.187	1.13
14	.379	2.28
15	.558	3.32
16	.756	4.58
17	.906	5.58

* THESE MEASUREMENTS WERE MADE AT THE GAUGE
USING A DIAL INDICATOR WITH .001 INCH INCREMENTS

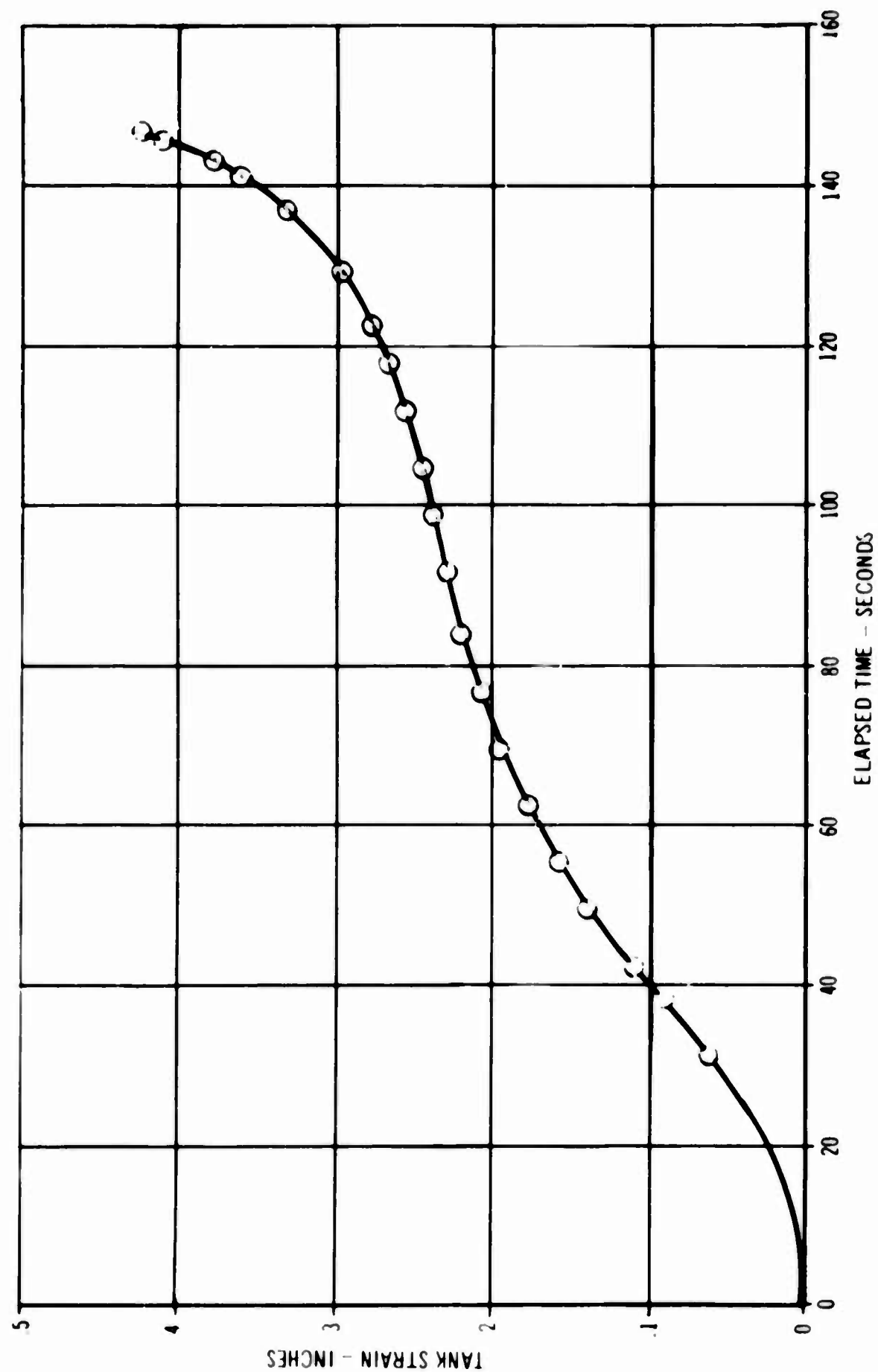
** THESE MEASUREMENTS WERE MADE WITH AN L&N
STRIP CHART RECORDER, S/N B62-75150-3-2

APPENDIX 2B

DEFLECTION GAUGE CALIBRATION



APPENDIX 2C
TANK STRAIN VERSUS ELAPSED TIME FOR
PRESSURE VESSEL T1-1A - TESTED AT -320°F (-196°C)



APPENDIX 20

TANK PRESSURE AND DEFLECTION DATA AT VARIOUS BURST TEST POINTS (ELAPSED TIME) FOR PRESSURE VESSEL TI-1A - TESTED AT -320°F (-196°C)

TEST POINT NO.	TANK PRESSURE			TANK DEFLECTION		ELAPSED TIME, SEC. **
	TRACE DEFLECTION INCHES	PRESS PSIG	CORRECTED PRESS. PSIG	TRACE DEFLECTION INCHES	TANK STRAIN IN/IN	
1	1.63	345	350	.37	.060	31.0
2	2.19	464	469	.57	.092	38.3
3	2.51	531	536	.73	.118	43.1
4	2.78	588	593	.84	.135	47.9
5	3.11	658	668	.96	.155	55.1
6	3.41	722	732	1.08	.174	62.3
7	3.67	777	787	1.18	.190	69.5
8	3.91	828	838	1.27	.205	76.7
9	4.10	868	878	1.35	.218	83.9
10	4.27	904	9.4	1.40	.226	91.1
11	4.42	936	951	1.46	.235	98.3
12	4.54	961	976	1.51	.243	105.5
13	4.64	982	997	1.55	.250	112.7
14	4.79	1014	1029	1.58	.255	117.5
15	5.16	1092	1107	1.70	.274	122.3
16	5.59	1183	1203	1.84	.296	129.5
17	6.18	1308	1328	2.03	.327	136.7
18	6.55	1387	1407	2.21	.356	141.5
19	6.72	1423	1443	2.32	.374	143.9
20	6.86	1452	1472	2.60	.419	146.3
*21	6.89	1459	1479	2.67	.430	147.3

* Point at which tank burst

** Chart Speed on L & N Recorder was 2.5 inches/min.